THE CENTRAL EXECUTIVE AND WORKING MEMORY: A DUAL-TASK INVESTIGATION OF THE N-BACK TASK

By

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Working memory is thought of as a cognitive process capable of briefly storing and manipulating information. Working memory consists of two domain-specific slave systems and a central executive, which is responsible for coordinating this simultaneous storage and manipulation of information and other *executive functions*. The *n*-back task is an experimental task that recently has been used to examine the neurophysiological substrates of working memory. In the *n*-back task, participants are presented with a series of stimuli and are to indicate whether the current stimulus matches the stimulus presented *n* stimuli back in the series, where *n* equals a number between 0 and 3. The results of these neuroimaging studies suggest that the *n*-back requires executive control at higher levels of *n*, but not at lower levels of *n*. This hypothesis was tested in 3 experiments in which participants were asked to perform versions of the *n*-back task concurrent with

secondary tasks designed to tax the various component processes of working memory. In experiment 1, an auditory-verbal *n*-back was paired with a visual-spatial version of the *n*-back. Relative to the single-task conditions, the dual-task conditions produced marked interference in the 2- and 3-back tasks, but not in the 0- and 1-back tasks. In experiment 2, the verbal and spatial *n*-backs were again paired but the length of time between stimuli was shortened in order to test a time-sharing hypothesis regarding the results of experiment 1. The accuracy results replicated the results of experiment 1, but the reaction time data showed interference in the 1-, 2-, and 3-back tasks. In experiment 3, the auditory-verbal *n*-back was paired with three visual tasks: a rhyme task, a random keypress task, and a mental rotation task. The results from these dual-task pairings indicate that the results from experiments 1 and 2 may reflect mere difficulty rather than the need for central executive resources specifically. Taken together the results of these experiments lead to the conclusion that the *n*-back task is a complex task that relies on multiple processes, some of which can be considered executive processes and others that are less executive in nature.

CHAPTER 1
INTRODUCTION

Executive functions appear central to any intelligent human behavior. Our ability to exert control over our attention, memory, and actions seems to be at the heart of our conception of ourselves as independent agents having free will, rather than merely reactive beings whose behaviors are shaped entirely by the environment in a simple stimulus-response fashion. This dissertation represents an attempt to examine the role of executive functions in working memory by pairing various versions of the *n*-back task, a working memory task that has been used recently in neuroimaging studies, with several secondary tasks intended to tax the multiple subcomponents of working memory.

Despite the clear importance of executive functions, the definition of executive function, or executive control, is elusive and depends on one's theoretical orientation or specific subfield within psychology. In fact, Eslinger (1996) states explicitly, "There is no universal definition of executive functions" (p. 380). Barkley (1997) underscores this more or less universal frustration by lamenting,

> ...what process is it that determines which goals will be selected, which plans, rules, and other sources of information will be considered in support of them, and what forms of private self-directed actions are necessary to generate that information? That process has been labeled the central executive... yet its specification has been left ambiguous. It has, alas become the black box within the

> black box that information processing models of cognition have been attempting to explain ...(pp. 201-202).

Regardless of the frustration and the lack of one universal definition, many attempts have been made to define executive function, and these attempts often include words and phrases such as planning, goal-directed behavior, strategy selection, temporal sequencing, anticipation, and preparation for action. On occasion, executive functions have been equated with those functions carried out by the frontal lobes of the brain, which proves to be an inadequate definition, at best. Welsh and Pennington (1988) include in their definition of executive functions, holding "a mental representation of the task, including the relevant stimulus information encoded in memory and the desired future goal state" (p. 202). Whichever specific definition of executive function is used, it is clear that executive functions lie at the intersection of memory and attention.

This project focuses primarily on one particular conceptualization of executive processes, namely the central executive of Baddeley's (1986) model of working memory. First some of the important ideas related to executive control are described, followed by a short sketch of Baddeley's model of working memory. Finally, some of the ways in which the central executive has been investigated are outlined.

Theories of Attention

Later in this paper, the central executive is referred to as an "attentional controller." Therefore what is meant by "attention" needs to be delineated so that the phrase "attentional control" has meaning. Most are familiar with the insightful quote from William James (1890):

> Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or

> trains of thought. Focalization, concentration of consciousness are of its essence. It implies withdrawal from some things in order to deal effectively with others. (pp. 403-404; cited in Abernethy, 1993).

Indeed, in everyday language, everyone does know what attention is. A teacher tells a daydreaming student to pay attention to her lecture. If we notice something new in the environment, that stimulus has grabbed our attention. If we are thinking about the meal we are preparing and then begin thinking about a bill that needs to be paid, we have turned our attention to the bills. If a task we are engaged in is difficult, we know that we must devote our full attention to it or else we are likely to make a mistake. We talk about a friend who has a short attention span. In these everyday expressions which none of us has any trouble understanding, we see the multitude of tasks that James so nicely summarized as "withdrawal from some things in order to deal effectively with others."

Unfortunately, despite the fact that everyone knows what attention is, no one really knows what attention is (Pashler, 1996). Within cognitive psychology, there is no one universal definition of attention. The only universally accepted idea regarding attention seems to be that it is limited. Attention has been equated and associated with a number of other concepts, including orienting, mental effort, and consciousness. As with executive functions, there are a multitude of paradigms and topics of interest that involve attention (e.g., selective attention, visual attention, auditory attention, spatial attention, sustained attention, vigilance, preparatory attention, and divided attention). The consideration of attention can be divided broadly into two classes: attention to our environment with the purpose of bringing information in through the senses; and attention to our goals and intentions with the purpose of carrying out some action, whether covert or overt. The efficient and accurate operation of both forms of attention is

necessary for carrying out complex tasks. The remainder of this section is a brief sketch of a number of theories of attention, some of which have considered both broad forms, and others that have considered only one form or the other.

Filter Theories

Filter theories have in common the assumption that some stages of information processing can proceed in parallel, while others are limited and must proceed serially. Generally, these theories divide information processing into three major stages: perceptual processes are those that convert raw sensory signals into symbolic mental representations, response processes are those that select responses and convert mental representations of responses into overt motor movement, and central processes are all other manipulations occurring between perception and response. In 1958, Broadbent introduced one of the most influential theories of attention. In his theory, attention operates early in the flow of information processing, prior to stimulus identification, to filter out irrelevant stimuli on the basis of physical features. A serious problem with Broadbent's theory is that subsequent evidence showed that in some circumstances people can identify certain stimuli, such as their own names, and can glean semantic information from a message even when presented in an unattended channel (Proctor & Dutta, 1995). In response to this, Norman (1968) proposed a late selection filter, in which the entire stream of incoming information is processed beyond the stage of stimulus identification and irrelevant information is filtered out at some later stage of processing. The major problem with this position is that messages presented in the unattended channel are so strongly attenuated. Triesman (1964) developed a more flexible version of an early filter model, in which the limiting structure was not an all-or-none filter, but rather was a selective attenuator. According to LaBerge (1995), most

contemporary researchers agree that late selection can occur on the basis of the individual's momentary goals and response tendencies. He further notes that event-related potential studies have shown attentional effects within the first 100 ms following a stimulus, and these effects have been localized to areas of the brain constituting the sensory projection areas. Thus, in some situations, at least, attention can be taken as modulating early perceptual processing. Attention, it seems, is perhaps more flexible than was assumed by early theorists.

Resource Theories

In part to incorporate into models of attention the flexibility that humans exhibit when performing attentional tasks, alternatives to filter theories that treat attention as a limited resource available to all processing stages have been proposed. One particular model proposed by Kahneman (1973) has been dubbed a unitary resource model because it proposes a single, undifferentiated resource common to all task demands. According to unitary resource models, the difficulty of a task is primarily what affects its demand for resources. Newly acquired or very difficult tasks require more resources, leaving no or few resources available for engagement in other tasks. An important related idea concerns the effect of training or practice on the need for resources. Schneider and Shiffrin (1977) describe two qualitatively different forms of information processing: controlled processing is effortful, attention-demanding, slow, and serial, and automatic processing is relatively effortless, free from attentional demands, fast, and parallel. A controlled process can become automatic, and thus require no or few resources, through extensive and consistent practice. Although Schneider and Shiffrin proposed controlled and automatic processing as a dichotomy, today most consider them instead to be the opposite ends of a continuum (MacLeod & Dunbar, 1988). A serious difficulty with

unitary resource theories, however, is that numerous studies have demonstrated that the extent to which two tasks interfere depends not only on the difficulty of the tasks, but also on the composition of the two tasks (Proctor & Dutta, 1995).

Instead of one unitary resource, then, others have proposed models that view attention as a collection of specialized pools of resources. These are the multiple resource theories. Wickens (1984), for example, defined resources in terms of a three-dimensional matrix consisting of stage of processing (perceptual, central, response); codes of perceptual and central processing (verbal, spatial); and the modalities of input (visual, auditory) and output (manual, vocal). Under multiple-resource theory, the extent to which two tasks will depends on the extent to which the two tasks require the same resources. A criticism of multiple-resource theories is that an essentially unlimited number of resources could be postulated, thus any pattern of results could potentially fit some version of multiple-resource theory, making the model untestable. Wickens himself foresaw this criticism and cautioned, "the explanatory and predictive power of the multiple-resources concept may be greatly diminished as the number of dimensions of separate resources proliferate" (p. 91). One way to avoid this criticism, perhaps, is to constrain the postulation of resources based on neuroanatomical and neurophysiological findings.

In 1984, Wickens posed the question, "What are resources?" and as an answer, he tentatively suggested that the concept of resources should be grounded in neuroanatomy and physiology; perhaps, he said, resources reflect the "actual competition for functional cerebral 'space' " (p. 90). Along these same lines, Klingberg (1998) sought to determine the neurophysiological basis for the behavioral interference observed when participants

attempt to perform two tasks at once by recording PET (positron emission tomography) scans while participants performed an auditory working memory (WM) task alone, a visual working memory task alone, and the auditory and visual WM tasks together in a dual-task situation. The auditory task consisted of presenting a series of tones of varying frequencies and asking participants to press a key when the current tone was of a lower frequency than the tone presented just prior to it. The visual task consisted of presenting a series of circular disks of varying luminance on a computer screen. Similar to the auditory task, the visual task was to press a key when the luminance level of the current stimulus was lower than the luminance level of the previous stimulus. The physical properties of the stimuli were adjusted based on prior testing so that the average d' in the single-tasks would be ≈ 3. Behaviorally, Klingberg found an interference effect, such that both d' and reaction time performance declined in the dual-task situation relative to the single-task situations. In the PET scans, he found that in the single-task situations, the visual and auditory WM tasks activated sensory-specific regions in occipital and temporal cortices, respectively, and also nonsensory-specific areas in the right dorsolateral prefrontal cortex (DLPFC) and in the left middle frontal gyrus for both tasks. In the dual-task situation, the right DLPFC and the left middle frontal gyrus again were activated but to a greater degree than in either of the single-task situations. Thus, in the two single-task situations, overlapping brain regions were activated by the two tasks. Furthermore, the pattern of activation was the same in the dual-task situation as in the single-task situation. This led Klingberg to postulate that there is no specific region of cortex responsible for dual-task situations specifically, but rather that behavioral interference arises from the overlapping brain regions needed for both tasks. He further

suggests that the behavioral interference could arise either because the two tasks require activation of the same population of neurons, or because the tasks could activate "different but interdigitated" (p. 599) columns of neurons which inhibit each other by local mechanisms. The spatial resolution of current PET techniques does not allow these two possibilities to be distinguished. Klingberg's results support Wickens' notion that resources reflect actual functional cerebral "space."

Klingberg's findings are in opposition to the findings of D'Esposito et al. (1995). D'Esposito et al. asked participants to perform a spatial mental rotation task in which stimuli were presented visually as a single-task and a semantic judgment task in which stimuli were presented auditorally as a single-task. Participants then performed these two tasks concurrently in a dual-task condition. Regional cerebral blood flow was measured using fMRI techniques. D'Esposito et al. found that the single-tasks primarily activated posterior regions and not the dorsolateral prefrontal cortex (DLPFC), but that the dual-task condition activated the DLPFC. To eliminate the possibility that the activation of the DLPFC was simply due to increased difficulty or increased mental effort in the dual-task condition rather than to the coordination of two tasks specifically, they conducted a second experiment. In the second experiment, participants performed the mental rotation task under two levels of difficulty: a slow stimulus-presentation condition and a fast-stimulus presentation condition. They found that the difficult condition produced more activation of the posterior regions involved in the easy condition but did not recruit frontal regions, including the DLPFC. From these results, they concluded that the DLPFC subserves the executive process of coordinating two tasks in a dual-task situation.

More recently, Bunge, Klingberg, Jacobsen, and Gabrieli (2000) sought to further investigate the neural substrates of dual-task coordination by asking participants to complete a sentence-verification task alone, a recall task alone, and then the two tasks concurrently while they measured cerebral blood flow using fMRI. Behaviorally, they did observe a dual-task cost in both accuracy and reaction time. In these tasks, they found that blood-flow activations were similar across all three trial types, but that in the dual-task condition, activations were more extensive and of greater amplitude. Critically, they found no region that was activated only by the dual-task condition. Similarly, Adcock, Constable, Gore, and Goldman-Rakic (2000) reported the neuroimaging results of two experiments in which two different dual-task comparisons produced no region generally activated by dual-task situations. They asked participants to complete an auditory verbal categorization task singly or in combination with either a visual mental rotation task (experiment 1) or a visual face-identification task (experiment 2). They found that the single-tasks produced different patterns of activation from each other and that all areas activated in the dual-tasks were also activated in the single-tasks. They conclude that executive processes may arise from the interactions among anatomically and functionally distinct systems engaged in component tasks rather than from a brain region generically dedicated to an executive system. Bunge et al. suggest that the apparent discrepancy between these two studies and the one by D'Esposito et al. is merely one of statistical thresholding and sensitivity of measurement. Citing past research that found prefrontal activation in mental rotation and verbal classification tasks performed singly (Cohen et al., 1996; Poldrach, et al., 1999, respectively), they believe that the

DLPFC likely was activated to a small degree by the single-tasks of D'Esposito et al., but to a degree that fell beneath the threshold for statistical significance.

Taken together, these studies support the notion that mental resources can be defined in terms of functional cerebral space. It may be that the behavioral interference observed in dual-task situations is due to competition for this space.

The Norman-Shallice Model

Norman and Shallice (1980/1986) propose a model of what they call attention to action, which consists of two major components. The first allows us to complete well-learned, routine thoughts and behaviors known as schemas. Schemas are activated by the perception of triggers in the environment. The association of trigger and schema is presumably learned gradually through repeated experience in the situations. The selection of which schema or schemas will be active at any particular point in time is carried out by contention scheduling which resolves conflicts through a process of lateral inhibition between competing schemas.

The second major component was termed the Supervisory Attentional System (SAS), and according to Shallice and Burgess (1993), it operates when schemas and contention scheduling would be inadequate. They indicate five situations that require the SAS:

1. Planning or decision-making,
2. Error-detection or error-correction,
3. Responses that are not well learned or routine,
4. Danger or great difficulty,
5. Overcoming habitual responses or resisting temptation.

These five specific situations were suggested from two more general types of situations. The first is the situation in which an error would be generated by the operation of schemas and contention scheduling alone, and the second is the situation in which no response would be generated due to the novelty of the situation. Shallice and Burgess (1993) justify the model with neuropsychological evidence from patients with lesions of the prefrontal cortex. These patients show deficient processing in situations that should require the SAS, such as the Tower of London, the Wisconsin Card Sorting Test, and the Stroop task. Another way of phrasing the Norman-Shallice model is to say that schemas represent relatively automatic processing and the SAS enables controlled processing.

The Anterior Attention System

The Norman-Shallice model is a purely cognitive system in the sense that it postulates functional divisions of the mind while making few claims regarding the brain. In contrast, Posner and Petersen (1990) have described an Anterior Attention System (AAS), which is primarily a neuroanatomical and neurophysiological model, making only a few claims regarding cognition. The AAS consists primarily of the anterior cingulate gyrus, the basal ganglia, the dorsolateral prefrontal cortex, and the medial thalamus. This system has rich interconnections with the hippocampus and entorhinal temporal cortex, giving it access to short-term memory storage and to processes involved in forming longer-term memories (Kandel & Kupferman, 1995). It also connects to primary motor cortex, giving it access to motor planning (Ghez & Gordon, 1995).

According to Carr (1992), the anatomical connections of the AAS make it particularly suited to executive control. He sites specifically Petersen et al.'s (1988) PET evidence that when noun-verb associations become practiced and stereotyped, activation

of the structures of the AAS decreases, while activation increases in representational cortex. Findings such as these dovetail nicely with the ideas of Norman and Shallice (1980/1986) and other dual-process theories of attention. It is possible that the AAS constitutes the neural substrates of the SAS.

Baddeley's Model of Working Memory

Working memory can be thought of as a system for the temporary storage and manipulation of information in order to carry out a wide range of complex tasks. Prior to Baddeley and Hitch's (1974) influential model of working memory, on which Baddeley (1986) has since elaborated, Atkinson and Shiffrin's (1968) conceptualization of memory and other so-called "modal" models were facing difficulties accounting for some of the data that was then emerging. According to Baddeley (1993), some of the data that required explanation beyond that provided by modal models included studies by Craik and Watkins (1973) which showed that the degree of learning wasn't necessarily related simply to rehearsal time; and a case study by Shallice and Warrington (1970) in which patients with severe STM deficits could nonetheless show normal long-term learning and few general cognitive deficits. Baddeley and Hitch attempted to resolve some of these difficulties by fractionating working memory into three subcomponents: two modality-specific slave systems (the phonological loop and the visuospatial sketchpad) and an attentional controller (known as the central executive). These components have been investigated by Baddeley and others to varying degrees over the intervening years, and each is described briefly next.

The Phonological Loop

The phonological loop itself has two subcomponents, according to the model (Baddeley, 1990). One is the phonological store and the other is an articulatory control process responsible for subvocal rehearsal. The phonological store appears to be capable of maintaining information for about two seconds (by which time the memory trace presumably has decayed, unless it is refreshed by the articulatory control process). Baddeley takes as evidence for the existence of and the characteristics of the phonological loop a variety of well-established memory phenomena.

The *phonological similarity effect* is that recall is impaired when the items of a list sound similar to each other relative to when the items sound different from each other. This effect is found whether the words are presented auditorally or visually, implying that people recode visually presented words into their constituent sounds in the process of trying to remember them. In contrast, it appears that, over a short delay, words that are semantically similar are recalled at the same rate as words that are semantically dissimilar (Baddeley, 1966).

The *word-length effect* is that recall is better for words that take less time to pronounce compared to words that take more time to pronounce. This effect seems truly to be related to pronunciation time rather than to the number of syllables, phonemes, or letters (Baddeley, Thomson, & Buchanan, 1975). From studies of the word length effect, Baddeley concluded that the capacity of the phonological store is based on the amount of verbal material that can be pronounced in approximately 2 seconds, rather than on some absolute number of "chunks" or "pieces" of information.

The *articulatory suppression effect* is the finding that recall for verbal material is reduced when one must repeat aloud a speech sound unrelated to the memory task (e.g.,

"the, the, the"). This technique eliminates the word-length effect for both visual and auditory presentation of stimuli, and it removes the phonological similarity effect for visually presented words, but not for auditorally presented words (Baddeley, Lewis, & Vallar, 1984).

The *irrelevant speech effect* occurs when recall of verbal material is disturbed by unattended speech sounds presented during study of the to-be-remembered items. This disruptive effect is even greater when the irrelevant speech comprises words that are phonologically similar to the words for recall (Salamé & Baddeley, 1982). It appears that the disruptive effect of sound is limited primarily to speech sounds. Salamé and Baddeley (1989) conducted studies of verbal serial recall in conditions of silence, noise, vocal music, instrumental music, and unattended speech. They found a decline in recall only in the vocal music and unattended speech conditions, and thus concluded that verbal recall was based on a speech-code rather than on some more generic acoustic code.

The Visuospatial Sketchpad

The visuospatial sketchpad of Baddeley's model is to some extent an analog of the phonological loop for visual and spatial information. While originally conceived of as a unitary construct, there is evidence that visual object information is stored in a manner separate from spatial information (Logie, 1995; Smith & Jonides, 1997). Much of the evidence regarding the visuospatial sketchpad comes from dual-task studies in which performance of a visual or spatial task interferes with the maintenance of visuospatial information in memory.

Numerous investigators have found a *visual similarity effect* in which confusions arise in memory for visually similar materials, similar to the phonological similarity effect. For example, Hue and Erickson (1988) reported visual similarity effects in short-

term memory for unfamiliar Chinese characters. Logie (1986) found a disruptive effect of *irrelevant visual input* on visual imagery, similar to the irrelevant speech effect. He asked participants to try to remember a series of words using either the one-bun pegword mnemonic, a device believed to rely on visual imagery, or a rote verbal rehearsal strategy. They performed these memory tasks alone and combined with irrelevant visual patterns presented on a computer screen, which they were instructed to do their best to ignore without closing their eyes or looking away. From these results, Logie concluded that visual input has privileged access to the visuospatial sketchpad similar to the manner in which auditory verbal input has privileged access to the phonological loop.

The Central Executive

The least-studied aspect of Baddeley's model is the central executive. Baddeley (1990) himself admits that this is probably because the slave systems present much more tractable problems for systematic investigation. Nonetheless, Baddeley (1996) and several other researchers (e.g., Kiss, Pisio, François, & Schopflocher, 1998; Morris and Jones, 1990) indicated that the central executive is undoubtedly the most important aspect of working memory in terms of its general impact on cognition.

As alluded to at the outset, defining the central executive is quite difficult, even for Baddeley (1996), who describes the 1974 version of the central executive as "little more than a ragbag into which could be stuffed all the complex strategy selection, planning, and retrieval checking." Further revision of the model led to a conceptualization of the central executive as an attentional controller heavily modeled after the SAS of the Norman-Shallice model. The definition of the central executive, then, has become a list of things that the central executive should do, including those situations given by Norman and Shallice (1980/1986) in which the SAS should operate.

Some of the things for which the central executive is responsible include the coordination of the two[1] slave systems and the retrieval of information from long-term memory. Another role ascribed to the central executive is that of attentional controller. Attentional control is defined broadly such that it can mean selecting among several streams of incoming information, selecting among multiple possible responses, or the allocation of cognitive resources to multiple ongoing tasks. On a conceptual level, considering the diversity of tasks that the central executive is purported to direct, a need to fractionate this aspect of working memory seems clear. Indeed, evidence to this effect exists, but there is little agreement regarding how many subcomponents exist and with what characteristics (Baddeley, 1998). In the next section, I address a sample of the ways in which the central executive has been studied, and in doing so examine these potential subcomponents of the central executive.

Investigations of the Central Executive

The Psychometric Approach

The psychometric approach (sometimes also referred to as the individual differences approach) to the study of working memory involves correlating performance on tasks that require the combined storage and manipulation of information with performance on traditional tests of intelligence or other tests of relevant cognitive skill, such as reasoning. For example, according to Bors and MacLeod (1996), moderate correlations have been found between tests of problem-solving, abstract reasoning, and

[1] Although Baddeley's model explicitly describes only two slave systems, if Baddeley's concept of how the mind works is correct, then there is a subtle implication that there should exist a slave system for every type of information that a person is capable of taking in from the senses or retrieving out of long-term memory, including, for example, non-verbal auditory information and semantic information (Smith & Jonides, 1997). Consistent with this notion, Crosson, et al. (1999) have found evidence for separable brain systems for semantic verbal working memory and orthographic verbal working memory in addition to phonological verbal working memory.

general intelligence on the one hand, and Daneman and Carpenter's (1980) measure of working memory span (in which participants hear sentences and must repeat back the final word of each sentence).

A representative example is a study by Duncan (1995). In this case, Duncan developed a task in which participants viewed a series of pairs of letters or digits presented continuously on a computer monitor. Their task was to report verbally either the letter on the right or the letter on the left as the stimuli were presented, and to ignore the letter on the opposite side and all numbers. At the start of each series, participants were instructed either to "watch right" or to "watch left," indicating which portion of the display they were expected to report. Participants continued this task until they were presented with either a plus symbol or a minus symbol in the center of the screen. A plus symbol indicated that they were to continue monitoring and reporting the letters presented on the side of the screen initially required, and a minus sign indicated that they were to switch sides of the display. So, for example, if the series had begun with the command, "watch right," a plus sign would indicate that they were to continue reporting letters from the right side of the display and a minus sign would indicate that they were to switch sides and begin reporting the letters from the left side of the screen, while still ignoring all numbers. Duncan found that a large portion of patients with frontal lobe lesions and a small portion of healthy adults continued to report the letters from the initial side of the display after the signal to switch sides, despite the fact that they remember and can verbally express the rule governing when to switch. Duncan regards this error as indicative of what he terms goal neglect, which is any disregard for a task requirement despite the fact that the requirement is understood and remembered, which can be taken

as a failure of the central executive. Goal neglect also can be regarded as a failure of prospective memory. As discussed in detail later, Marsh and Hicks (1998) have demonstrated that prospective memory relies on the operation of the central executive. Duncan administered to a wide range of healthy adults, including young, middle-aged, and elderly this task and the Cattell's Culture Fair test, a standard test of *fluid intelligence*, that is, intelligence that is involved in novel problem solving and that is less dependent on acquired knowledge. Duncan found that, in all age groups, goal neglect was seen very rarely in those whose Culture Fair score was one standard deviation or more above the mean, but it was almost always seen in those whose Culture Fair score was one standard deviation or more below the mean.

The preceding study and others like it can be taken as evidence that intelligence reflects the operation of a central cognitive processor, such as the central executive of Baddeley's working memory model. But as Baddeley (1996) points out, this leads back to questions of whether intelligence is better considered as a single general capacity (such as Spearman's *g*) or as a number of specific capacities. This question can also be asked regarding the central executive. It seems clear that Duncan's task (and other "executive" tasks) share some fundamental similarities with and require cognitive skills and operations similar to the tasks that make up the measurement of intelligence. Thus, the correlation between "fluid intelligence" and "executive processes" in and of itself is neither surprising nor terribly informative. What might be more useful for future psychometric investigations of the central executive would be a more detailed look at the relationship between the contributions of individual differences to the various tasks described in the next two sections.

The Neuropsychological Approach

The neuropsychological approach to the study of executive functions is to compare the performance of patients who have lesions or diseases affecting brain functioning with the performance of healthy control subjects on tasks presumed to require the intact operation of the central executive. As previously mentioned, one approach to studying executive processes is to define "executive functions" as those functions carried out by the frontal lobes. Indeed, references are often made to a "frontal lobe syndrome," a pattern of behavioral deficits likely to result from damage to the frontal lobes. There is ample evidence that disorders of executive functions are associated with damage to the frontal lobes (e.g., Shallice and Burgess, 1993), but difficulties with executive functions can arise from damage and disease affecting other brain regions as well. As Baddeley (1996) points out, "the frontal lobes constitute an extremely large area that almost certainly has multiple functions that are as yet poorly understood" (p. 6). Further, it is likely that regions other than the frontal lobes play an important role in executive processes. Duncan (1995) argues that

> … [Executive control] is heavily dependent on the frontal lobe and therefore disturbed by frontal lesions, but this is not to say that the frontal lobe or specific frontal regions are entirely responsible for it. It remains an open question how such general functions might arise from the combined activity of separate frontal regions and the many cortical and subcortical structures with which they interact (p. 731).

For these reasons, Baddeley argues against the term "frontal lobe syndrome" and instead advocates use of the term "dysexecutive syndrome" to describe the behavioral deficits that often accompany frontal lobe damage. Several common clinical tasks have been considered tests of executive functions, including tasks measuring verbal fluency (e.g., the Controlled Oral Word Association test), the Stroop, the Wisconsin Card Sorting Test

(WCST), the Continuous Performance Test, and the Towers of Hanoi and London. For the sake of brevity, only a few of these tasks are discussed in detail.

Stroop

The Stroop task is one common clinical test that is frequently considered a test of executive function. The task requires the participant to name the color of either conflicting color words (e.g., the word "blue" shown in red) or neutral stimuli (e.g., colored X's or non-color words). Successful performance requires one to inhibit the prepotent or relatively automatic response of reading the color word, and this inhibition is manifested in increased response time and error rate in the conflicting condition relative to the neutral condition. This is the so-called Stroop effect.

Vendrell et al. (1995) conducted an extensive investigation of performance on the Stroop task of 32 patients with a variety of frontal lobe lesions due to head injury, stroke, or brain tumors. In concert with the idea that the frontal lobes fulfill diverse functions, not all patients showed abnormal Stroop performance. In fact, 71% of the patients performed normally on the Stroop task. Of those whose Stroop performance was impaired, lesions of the anterior cingulate were related to slowed response times, and lesions of the lateral prefrontal cortex were associated with a larger Stroop effect in both response times and error rates when compared to the performance of healthy controls.

In accord with Duncan's (1995) sentiments expressed above, disorders of the frontal lobe are not the only ones that disrupt performance on the Stroop task. Disorders of the basal ganglia, such as Huntington's disease (Brandt, 1991) and Parkinson's disease (Brown & Marsden, 1991) have also been implicated in increased interference in the Stroop task. Further, patients with some forms of schizophrenia, in which there is a disturbance of the neurotransmitter systems involved in the bi-directional connections

between the frontal lobes and the basal ganglia, also show impaired performance on the Stroop task (Cohen & Servan-Schreiber, 1992).

Wisconsin Card Sorting Test

The purpose of the Wisconsin Card Sorting Test (WCST) is to assess the ability to form abstract concepts, to shift and maintain set, and to utilize feedback. The task is complex and requires high-level problem solving abilities including strategic planning, goal-oriented behavior, and the ability to modulate impulsive responding. In the WCST, four different stimulus cards are placed in front of the participant. The faces of the four cards show 1) one red triangle, 2) two green stars, 3) three yellow crosses, and 4) four blue circles. The participant is given a deck of 128 response cards that have designs similar to the stimulus cards, varying in color, form, and number. The participant is asked to match each card in the deck to one of the stimulus cards but is not informed on what basis (color, form, or number) the cards are to match. The participant is given feedback regarding the accuracy of each response and on the basis of that feedback must determine the rule upon which matching should take place. Once the participant has demonstrated mastery of a category by making ten successive correct matches, the category switches without warning. For example, at the beginning of the test, the cards are to be sorted on the basis of color. Once the participant has sorted ten consecutive cards correctly on the basis of color, then the sort principle shifts to form and matching the response card to the stimulus card on the basis of color will now result in feedback indicating a wrong response. The task continues until the participant has successfully completed six categories (color, form, and number, each twice) or until all 128 response cards have been sorted, which ever comes first. There are a number of dependent measures this task produces. A few of the most common are categories completed, which

can range from 0 (if the participant never figures the task out) to 6 (after 6 categories the task is terminated), the total number of trials to complete the first category, and number of perseverative errors. A perseverative error occurs when a participant continues to sort on the basis of a previously achieved category despite feedback that sorting on that basis is now considered wrong.

According to the literature, the WCST is often associated with frontal lobe damage, although some claim this association is too vague to be clinically or theoretically useful (Anderson, 1995). Several studies have implicated the involvement of the frontal lobes in the WCST, including the now classic study by Milner (1963) in which she found that patients with lesions of the dorsolateral prefrontal cortex demonstrated impaired performance on the WCST, especially in errors of perseveration, indicating a difficulty in shifting set, while patients with orbitofrontal and posterior lesions did not show this impaired performance. More recently, Arnett, et al. (1994) conducted a study of patients with frontal lobe lesions resulting from multiple sclerosis and found that the WCST was sensitive to frontal damage. However, Anderson, et al. (1995) examined 68 patients with traumatic brain injury and found that while WCST performance was impaired by brain damage, it was not related to volume of focal frontal damage, to the presence or absence of frontal damage, nor to the degree of atrophy. Consistent with the idea expressed earlier that executive functions likely depend on the interaction of cortical and subcortical systems, impairment on the WCST has been observed in a number of neurologic conditions including Parkinson's disease, Korsakoff's syndrome, and schizophrenia (Kolb & Whishaw, 1995). Spreen and Strauss (1998) presented a brief review of the literature on the WCST and concluded

> Overall, the WCST cannot be used by itself to predict a focal frontal lesion. Rather it may be more plausible to conceive of the WCST as a complex measure of executive functioning that is not linked to a single neuroanatomical region, but to the integration of multiple brain regions, of which the frontal lobes are important constituents (p. 224).

Continuous Performance Tasks

Another task often regarded as requiring executive control is the Continuous Performance Task (CPT), which exists in several common versions, such as the X-, the AX-, and the XX- (also sometimes referred to as the "identical pairs" or "IP" version). In all versions, participants view a series of letters presented one at a time at a constant rate on a computer screen. In the X-CPT, the participant is to press a key whenever a target (e.g., the letter X) appears. In the AX-CPT, the task is to press a key when a target (e.g., the letter X) immediately follows a cue (e.g., the letter A). In the XX-CPT, the participant is to press a key whenever the current stimulus matches the stimulus immediately preceding it (as will be expounded upon later, this is simply another name for the "1-back" task).

Rueckert (1996) investigated the performance of patients with right or left frontal lobe lesions and healthy age-matched controls on the X-CPT. She found that patients with right frontal lobe lesions missed more targets than did either the controls or the patients with left frontal lobe lesions. Interestingly, in a separate study (Rueckert, 1998), she found that patients with posterior cortical lesions (regardless of laterality) performed similarly to right frontal lobe patients on the X-CPT, but only when the presentation rate of the stimuli was relatively fast. She interpreted this similarity between the posterior patients and the frontal patients at the relatively fast stimulus presentation rate in terms of a previous finding that patients with posterior lesions habituate to visual displays more

quickly than controls. The fact that both frontal and parietal patients showed impaired responding to targets led Reuckert to conclude that, "attending is controlled by a distributed network that includes the frontal and posterior parietal cortices, and probably several subcortical structures as well" (p. 659).

In addition to studies of patients with brain lesions, the CPT has been studied in non-patients using imaging techniques. For example, Rezai et al. (1993) used single photon emission tomography (SPECT) with the xenon-inhalation technique to compare activation of regional cerebral blood flow (rCBF) in frontal brain regions during the performance of the AX-CPT in normal individuals. They found that performance of the task produced activation in the medial frontal lobes bilaterally with somewhat greater activation on the left side. Although the spatial resolution of SPECT techniques doesn't permit detailed analysis of regions activated, a medial frontal activation would include the anterior cingulate gyrus, which has been implicated in other executive tasks.

The CPT has also been extensively studied in schizophrenics. For example, Cohen, Braver, and O'Reilly (1996) studied the performance of unmedicated schizophrenics on the AX-CPT in which they manipulated the delay between the cue and the target. They found that the schizophrenics showed a significant increase in AX misses and BX false alarms (where "B" represents any non-"A" letter) compared to normal controls, but only at the long delay and not at the short delay. They take this as an indication that the patients failed to maintain a representation of the context throughout the longer delay interval, which is one of the roles posited for the central executive. Taken together, these studies support the idea that executive control is not

carried out by the frontal lobes alone, but rather by a network or networks of cortical and subcortical regions working in concert.

The neuropsychological approach to studying executive functions involves some difficulties. The major difficulty is in the lack of specificity of many of the so-called "executive" tasks. It's likely that successful completion of tasks such as the Stroop, the WCST, and the CPT, require multiple executive functions as well as multiple functions not so closely related to cognitive control (Pennington, Bennetto, McAleer, & Roberts, 1996). Additionally, it is all too common in these types of studies for patients to be poorly specified, so that patients with "frontal" lesions are compared with patients with "posterior" lesions, for example. Likewise, there are qualitatively different forms of schizophrenia symptoms, as well as varying degrees of severity of schizophrenia, Huntington's disease, and Parkinson's disease, yet it is common in studies of executive functions that these types of distinctions among patients are not made, but rather that "patients" are simply compared with "controls." Finally, there is the ever present caveat that lesion data do not tell us what the injured part of the brain did, so much as they tell us what the rest of the brain can no longer do, or does differently, without the injured part.

The Experimental Approaches

A third approach to the study of the central executive is the experimental approach, or rather more appropriately, the experimental approaches. These approaches typically investigate the operation of the central executive in healthy young adults (although some developmental and aging studies have been conducted) and utilize the methodologies of experimental cognitive psychology. Consistent with the idea that the central executive is not truly a unitary concept, there have been numerous experimental

paradigms that address the existence and the nature of the central executive, each of which examines a different proposed function of the central executive. Again, out of a concern for brevity, only a few of the many experimental paradigms will be described here.

Random Generation

The random generation task dates back at least to Baddeley's own dissertation work (Baddeley, 1966; cited in Baddeley, 1993). In this task the participant is instructed to imagine that the letters of the alphabet, for example, are written on identical slips of paper that are placed in a hat, which is then shaken to mix the slips of paper. The participant's task is to imagine that he or she reaches into the hat, draws a letter, speaks the name of the letter, returns the drawn letter to the hat, shakes the hat and then repeats the sequence. In this way, the participant is asked to produce a series of "random" letters, and when given sufficient time, people are capable of producing a string that approximates randomness. Baddeley's original study found that redundancy (repeating a letter more often than would be expected by chance) and stereotypy (producing well-learned sequences of letters, such as "ABC" or "USA") increased with an increase in the rate at which production was demanded. Further, he found that the maximum possible generation rate, which still produced acceptably random responses, decreased as the number of possible alternatives increased, up to about 8 alternatives, after which the function leveled off. Baddeley and his colleagues have developed a number of versions of this task, including verbal response versions involving either letters or numbers, and a manual response version, in which the participant is asked to produce a string of "random" keypresses.

Baddeley, Emslie, Kolondy, & Duncan (1998) conducted a series of six experiments to answer some specific questions regarding the nature of the manual-response version of the random generation task. The first experiment was simply a verification that the manual-response version produced the same pattern of results as the verbal-response versions, which it did. The second experiment examined the extent to which random generation could be considered a reflection of a limited capacity working memory system. Participants performed the keyboard generation task concurrent with a verbal digit-span task of various levels of memory load. As expected, the randomness of responses decreased as memory load increased. The third experiment sought to examine the extent to which the random keyboard generation task requires the operation of the central executive. In order to test the hypothesis that it does, Baddeley, et al. combined the keyboard generation task with three other secondary tasks in a dual-task paradigm. The three secondary tasks were 1) counting, a task involving well learned responses that should not require executive processes, 2) verbal fluency, a task typically believed to involve executive processes because it is often impaired when other symptoms of the dysexecutive syndrome are present, 3) and a test of fluid intelligence consisting primarily of verbal reasoning questions, also a task believed to engage the central executive heavily. The verbal fluency task consisted of generating examples of members of semantic categories, and the fluid intelligence test was constructed from Heim's AH2 and AH3 tests of general reasoning. The randomness of keypresses was not affected by concurrent counting, but randomness decreased when verbal fluency was the secondary task. A decrease in randomness was also observed when the reasoning task was the secondary task, and this effect was even more pronounced for the reasoning task than it

was for the verbal fluency task. These results provide support for the idea that the random generation task requires the operation of the central executive. The fourth experiment again combined random keypress generation with counting and verbal fluency, but also combined the random generation of keypresses with the verbal random generation of digits in order to further explore the extent to which random generation provides an index of a general working memory system. Because random generation of both digits and keypresses should require the operation of the central executive, and further, are so similar that they should require the same subprocesses of the central executive, it was expected that the concurrent performance of the two should lead to a catastrophic breakdown of performance. That, however, is not what happened, rather verbal random generation interfered with manual random generation significantly *less* than did verbal fluency.

Baddeley and his colleagues (Baddeley, 1996; Baddeley, Emslie, Kolodny, and Duncan, 1998) explain the pattern of results obtained with the random generation tasks in terms of the Norman-Shallice model. When asked to produce a string of letters, for example, one's habitual letter retrieval schemata, such as reciting the alphabet or common acronyms, are activated, however because the task requires randomness, the intervention of the SAS is necessary to disrupt the action of these schemata. Baddeley presumes that each response in a random generation task involves setting up a retrieval plan, executing it, checking the output of the retrieval plan, and if the output is sufficiently "random," then producing the output as a response. The decrease in randomness at higher response speeds, then, occurs as a result of the time needed to switch retrieval plans. The fact that the verbal-response random generation task does not

interfere to a large extent with the manual-response random generation task may be due to a strategy whereby the participant in the dual-task situation may not switch retrieval plans for the verbal task at the same time as the manual task, thus permitting relatively spared performance in both tasks.

In their 5th and 6th experiments, Baddeley, Emslie, Kolodny, and Duncan (1998) attempted to test this retrieval-plan-switching hypothesis by having participants perform the manual response random generation task in yet another set of dual-task situations. This time, the secondary tasks were counting aloud, reciting the alphabet, and alternating between reciting the alphabet and counting aloud (e.g., "A-1-B-2-C-3-D-4," etc.). This alternating task was considered to be a verbal analog of the Trails B subtest of the Halstead-Reitan battery. The Trails B task consists of an array of letters and numbers printed on a piece of paper. The participant's task is to use a pencil to draw a line from 1 to A to 2 to B and so on. Patients with lesions of the frontal lobes often perform poorly on this task. Baddeley et al.'s Trails B verbal analog was thought to impose a minimal memory load and yet to require the switching of retrieval plans as one alternates from letter to number. They found that while counting or reciting the alphabet alone did not affect the randomness of the keypresses, the Trails B verbal analog task led to a reduction in randomness in the keypresses. They therefore concluded that random generation requires the operation of the central executive due to its demand for the constant switching of retrieval plans.

Executive Control and Prospective Memory

Prospective memory is defined as remembering to do something in the future, and researchers in the area typically distinguish between event-based prospective memory, in which remembering is cued by some stimulus in the environment (e.g., "When John calls,

I need to ask him about that book"), and time-based prospective memory, in which remembering must be based solely on the passage of time (e.g., "John gets home from work in an hour. I need to call him about that book in an hour"). Marsh and Hicks (1998) conducted five experiments investigating the relative contributions of the phonological loop, the visuospatial sketchpad, and the central executive of Baddeley's model of working memory to event-based prospective memory. In all five of their experiments, they used as their prospective memory task the Einstein-McDaniel task, in which participants are presented with three words one at a time at a fairly slow pace and are asked to recall in any order those three words at the end of a 6.5 sec retention interval. Additionally, the participant is to press a key anytime that a member of some specified category (e.g., fruit) is presented during the study phase. It is this last part which constitutes the prospective memory task. The five experiments conducted by Marsh and Hicks consisted of pairing the Einstein-McDaniel task with several different secondary tasks considered to load on various portions of working memory. There were two levels of each concurrent task, high load and low load, which they manipulated between participants, and an additional group of participants who performed the Einstein-McDaniel task without a concurrent task as a control. They also administered singly the Wisconsin Card Sorting task and a verbal fluency task, two common neuropsychological tasks considered to be measures of executive processes, in an attempt to correlate performance on these tasks with performance on the prospective memory task.

In Experiment 1, the Einstein-McDaniel task was combined with the Star Counting task (SCT), a task previously shown to require operation of the central executive. In the SCT, the participant is presented with a two-digit start number and an

array consisting of mostly asterisks interspersed with plus signs and minus signs. The participant is to begin with the start number and count aloud either forward or backward (depending on whether the first symbol is a plus or a minus) by some specified amount for each asterisk until another plus or minus symbol is reached, in which case the participant may be required to switch direction of counting (i.e., if the participant began with a plus symbol, upon reaching a plus symbol in the array, he or she was to continue counting forward, and upon reaching a minus symbol, he or she was to switch to counting backward). In the high load condition, the numbers by which they were to count changed from trial to trial and could be different for forward versus backward counting within a trial. For example, on trial one the participant might be instructed to count forward by threes and backward by twos, and then on trial two he or she might be instructed to count forward by twos and backward by ones. In the low load condition, participants counted by twos consistently, both across trials and for both forward and backward counting. Compared to the group who performed the Einstein-McDaniel task alone, performance on the prospective memory task was significantly worse for those in the high load condition, but prospective memory for those in the low load condition was the same. From these results, Marsh and Hicks conclude that, to the extent that the high load version of the Star Counting task requires the operation of the central executive, prospective memory may depend in part on those same executive resources.

In Experiment 2, participants performed the Einstein-McDaniel task concurrent with the random generation of digits. In the high load version of the random generation task, participants generated digits at a rate of one per second, and in the low load version, the rate of generation was slowed down to one per 1.5 sec. Compared to those in the

control group, participants in the high load group responded to the prospective memory events significantly less often, but those in the low load group performed just as well on the prospective memory task as did those in the control group. Marsh and Hicks considered Experiment 2 to be a replication of Experiment 1 using a different central executive task, and they take these results as more evidence that prospective memory depends upon executive processes.

It is possible to explain the result of both Experiments 1 and 2 in terms of Baddeley's (1996) idea of the need to switch retrieval plans. The high load condition of the SCT required participants to switch from counting forward to counting backward and to increment by different amounts in these two directions. The low load condition should require the switching of retrieval plans much less because the number by which participants counted was constant. That is, when one switches from counting forward to counting backward he or she merely recalls in reverse order numbers just generated. Moreover, the number by which participants counted in the low load condition (i.e., two) and the fact that this number was consistent from trial to trial both contributed to a considerably lower overall level of novelty in the low load condition as compared to the high load condition. Recall that novel tasks require executive processes (or the intervention of the SAS) whereas less novel tasks do not. Similarly, the faster pace of random generation in the high load condition of Experiment 2 can be seen as requiring more frequent switching of retrieval plans, while the slower pace of the low load condition required less frequent switching and permitted more time for the switching to occur and for attention then to return to the prospective memory task, resulting in a higher level of performance on both tasks.

Experiments 3, 4, and 5 all involved tasks that required the operation of the phonological loop and the visuospatial sketchpad while requiring little or no intervention from the central executive. In Experiment 3, the concurrent task was the overt rehearsal of three (low load) or six (high load) monosyllabic words. There was no effect of load on performance of the prospective memory task. In Experiment 4, the concurrent task was a spatial sequential tapping task which loads heavily on the visuospatial sketchpad, but which also contains a requirement that participants monitor their behavior and plan spatial motor movements, components which should require the operation of the central executive. The low load version of the tapping task had participants perform the same sequence of taps from trial to trial, while the high load version had participants switch between two opposite sequences of taps each trial. Similar to performance in Experiments 1 and 2, participants in the high load condition responded to significantly fewer prospective memory events, while those in the low load condition did not differ from the control group. This is consistent with the idea that the high load version of this visuospatial task contained components which required operation of the central executive and that this occupation of the central executive produced a decline in prospective memory performance. Experiment 5 involved the concurrent performance of a visuospatial task that was developed specifically to minimize the need for the operation of the central executive and which has been shown previously to demand visuospatial resources. The task was to watch a dynamic display of colored pixels continuously turning on and off. Marsh and Hicks described the display as "much like dynamic visual noise" (p. 344). In the high load condition, the display colors changed every 4 seconds,

and in the low load condition the colors did not change. Again, as in Experiment 3, there was no effect of load on prospective memory performance.

In addition to the experimental manipulations of Experiments 1-5, Marsh and Hicks also measured participants' performance on the Wisconsin Card Sorting Task and on verbal fluency. They found that performance on these two tasks correlated with performance on the event-based prospective memory tasks, regardless of load condition. Based on these correlations, and on the results of all five experiments, Marsh and Hicks concluded that event-based prospective memory depends on the successful operation of the central executive, but that it doesn't depend to any large degree on the phonological loop or the visuospatial sketchpad. In terms of prospective memory outside of the laboratory, this can be taken to mean that whether or not a person responds to an environmental cue to carry out a previously formed intention depends in large part on what cognitive operations are being engaged at the time the person encounters the environmental cue.

Updating Working Memory

Morris and Jones (1990) define memory updating as the process of modifying an existing representation in memory in order to incorporate new information. They give as an example of updating long-term memory the case of needing to remember your new telephone number when you have moved. They note that memory updating is generally not a destructive process as the previous information (i.e., your old phone number) can often be recalled, although there is a clear recency effect. Morris and Jones hypothesized that the central executive may be responsible for the dynamic aspects of the updating of working memory. In order to test their hypothesis, they had participants perform a memory updating task concurrent with two different tasks known to disrupt the operation

of the articulatory loop: articulatory suppression and listening to irrelevant speech. The memory-updating task consisted of the presentation of lists of letters one letter at a time on a computer screen. The lists could be 6, 8, 10, or 12 items long. Lists of different length were presented in random order so that the specific length of a list on any given trial was unknown to the participant at the start of each trial. The task was to recall in serial order the last six items presented prior to a recall cue. Because the task was to recall the 6 most recently presented items, it was believed that the task required the updating of working memory either 0, 2, 4, or 6 times for lists of length 6, 8, 10, and 12, respectively. Presumably, as items in the lists longer than 6 were presented, the participant should drop the oldest item from the beginning of the list and add the most recently presented item to the end of the list. This memory updating task was either performed alone or paired concurrently with repeating the word "the" continuously (articulatory suppression) or listening to irrelevant speech. They found that serial recall performance declined when paired with articulatory suppression and irrelevant speech, relative to serial recall performed alone, but that this effect did not interact with the number of updates required (i.e., list length). This lack of an interaction they took as evidence that the updating component of the running memory task depended not on the articulatory loop, but on the central executive.

The *n*-Back Task

The *n*-back task is another task that has recently been utilized to examine working memory (Smith, Jonides, Marshuetz, & Koeppe, 1998). In the *n*-back task, the participant views a series of stimuli presented at a constant rate on a computer monitor. The participant's task is to press a key whenever the current stimulus matches, usually on

the basis of form or spatial location, the stimulus that was presented *n* stimuli back in the series, where *n* equals a number between 0 and 3.

The *n*-back task has been investigated most extensively in the context of cognitive neuroscience studies of working memory utilizing Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI) techniques in attempts to determine what regions of the brain are active in the various different types of working memory tasks, such as verbal working memory tasks and visuospatial working memory tasks, as well as the subprocesses involved in each of the slave systems of Baddeley's model. For example, Awh, et al. (1996) measured rCBF using PET techniques while participants performed a 0-back search control condition, a verbal 2-back working memory condition, and a rehearsal control condition. Based on subtractions of the two control conditions from the working memory condition, they concluded that separate brain regions mediate verbal rehearsal and storage of verbal material. Verbal rehearsal activated the supplementary motor cortex and Broca's area, and simple storage of verbal material activated posterior parietal cortex.

The *n*-back task is particularly well suited for neuroimaging studies because it permits systematic variation of one parameter of the task. This parametric variation allows the researchers to avoid using the subtraction technique in which images taken during a control task are subtracted from images obtained during performance of the experimental task. In the *n*-back task, memory load can be systematically increased from 0 to 3, which leads to the prediction that as memory load is increased, discrete brain areas involved in the task will show a systematic increase in activation. In a follow-up to the PET study conducted by Awh et al. (1996), Cohen et al. (1997) conducted an fMRI

experiment in which participants performed the 0-, 1-, 2-, and 3-back tasks. The trials within each task were presented at a slow rate, which permitted the recording of multiple fMRI scans per trial. This technique allowed them to investigate the temporal dynamics of the brain regions involved in the various conditions. Both the posterior parietal region, found by Awh et al. to be responsible for storage of verbal material, and Broca's area, found by Awh et al. to be responsible for verbal rehearsal, showed a monotonic increase in activation with increases in level of *n*. Importantly, they also found that the activation of the parietal area was more sustained across the trial than was the activation of Broca's area. They interpreted these different temporal patterns of activation as further evidence in favor of the dissociation between verbal storage and rehearsal processes.

In a number of studies, Smith and Jonides and their colleagues (e.g., Awh, et al., 1996; Jonides, et al., 1997; Smith & Jonides, 1997; Smith & Jonides, 1998; Smith, Jonides, Marshuetz, & Koeppe, 1998) have used the *n*-back task in PET and fMRI studies of both verbal and visuospatial working memory. The patterns of results from these studies converge nicely with each other, and indicate that bilateral activation in the dorsolateral prefrontal cortex (DLPFC) increases when the 2- and 3-back tasks are performed, but it is not activated nearly as much when the 0- and 1-back tasks are performed. These patterns of bilateral activation of the DLPFC are consistent whether the task was a verbal, spatial, or object task. The DLPFC has been implicated in both lesion studies and other neuroimaging studies as involved in "executive processes." Smith & Jonides (1997) speculate that in the 2-back and 3-back tasks, the DLPFC is being recruited in service of the temporal sequencing of the stimuli, a necessary process for successful performance of the task, and one of the functions possibly controlled by

the central executive. In the 0-back and the 1-back tasks, this temporal sequencing need not be performed in order to succeed at the task. This suggests that rather than being a true parametric variation, the increase in memory load actually creates at least two qualitatively different tasks: one in which the operation of the central executive is required (i.e., the 2- and 3-back tasks) and one in which it is not (i.e., the 0- and 1-back tasks).

The Present Investigation

One of the difficulties with the *n*-back task is that due to its relative newness, the cognitive processes required for the task have not been extensively explored. The task has been used primarily in neuroimaging studies, and so the processes presumed to be operating in the task are inferred based on patterns of brain activation rather than having been experimentally verified. To remedy this, the task needs to be explored more extensively from an experimental cognitive psychology perspective. The present series of experiments have been an attempt to experimentally verify the need for executive processes in the various versions of the *n*-back task. The major hypotheses being tested were 1) that just as neuroimaging evidence indicates that the DLPFC activates in service of the 2- and 3-back tasks, these two tasks should indicate behaviorally a need for executive processes, and 2) the 0- and 1-back tasks should indicate no or little need behaviorally for executive processes, just as these two tasks activate the DLPFC only to a very small degree.

CHAPTER 2
EXPERIMENT ONE

In the dual-task paradigm participants are asked to complete two tasks concurrently while measures of performance in both tasks are recorded. From the point of view of the resource theories of attention, performance on one or both tasks will decline in the dual-task situation relative to the single-task situation to the extent that the total demand for resources exceeds the supply. In this manner, participants' performance in the dual-task paradigm can inform us regarding the extent to which two tasks compete for similar resources.

The dual-task paradigm has been useful in examining the operation of various components of Baddeley's (1986) working memory model, including the phonological loop (Baddeley & Logie, 1999), the visuospatial scratchpad (Logie, 1995), and the central executive (Baddeley, Emslie, Kolodny, & Duncan, 1998). The present experiment also made use of this paradigm by pairing two *n*-back tasks: a verbal *n*-back and a spatial *n*-back. These two tasks should be maximally similar in their need for executive resources, and yet maximally dissimilar in their need for other resources. As long as different input and output modalities are utilized for the two tasks then any interference observed in the dual-task conditions would be due to competition for executive processes.

It was expected that, just as Smith and Jonides (1997) found minimal activation of the DLPFC in the 0- and 1-back tasks, there would be minimal interference when the 0-back verbal and spatial tasks were paired and when the 1-back verbal and spatial tasks

were paired. The 2- and 3-back tasks, on the other hand, produced significant activation of the DLPFC in the Smith and Jonides studies, and thus, were expected to produce substantial interference when the verbal and spatial tasks were paired.

An additional consideration in any task concerns the role of individual differences in performance of the task. The n-back is considered to be a working memory task, and so it would be reasonable to expect that working memory span differences may affect one's ability to carry out even the single-tasks, and further that those with high working memory spans may be better able than those with low working memory spans to coordinate two working memory tasks in a dual-task situation. In order to explore this possibility, two measures of working memory span were gathered: Daneman and Carpenter's (1980) listening span test was considered a measure of verbal working memory span and a modified version of the Corsi Block-tapping test (Corsi, 1972) was considered a measure of visuospatial working memory span.

Method

Participants

Thirty undergraduates (15 male) at the University of Florida participated in partial fulfillment of a course requirement. Participants' ages ranged from 18 to 29 (M = 21, SD = 2.7) years. All had normal or corrected-to-normal vision and normal hearing.

Materials and Apparatus

Verbal working memory span task

The sentences from Daneman and Carpenter's (1980) listening span task were used verbatim. The test is constructed of 54 unrelated sentences, 13 to 16 words in

length. Each sentence ends in a different word. The stimuli for this test are contained in the Appendix.

Visuospatial working memory span task

The apparatus from the Corsi block-tapping task (Corsi, 1972) was utilized. A diagram of this apparatus is shown in Figure 1 of the Appendix. The apparatus consists of nine 2.54 cm cubes arranged irregularly on a 23 x 28 cm board. The entire apparatus is black. The cubes are labeled with yellow numbers on the side of the apparatus that faces the experimenter. These labels are not visible to the participant. The original sequences from the Corsi task were modified so that this task would parallel Daneman and Carpenter's (1980) listening span task. To that end, sequences were constructed consisting of 4 blocks each and organized into sets of 2, 3, 4, 5, and 6 sequences. The sequences used are also given in the Appendix.

***N*-back tasks**

An IBM-compatible Pentium computer in a Windows environment presented all stimuli and recorded all responses. Auditory stimuli were presented over earphones binaurally and consisted of 8 phonologically dissimilar consonants spoken by a female voice and lasting for 280 ms each. The visual display was presented on a 17-inch computer monitor and was divided into 2 invisible concentric circles, the larger of which subtended 9 degrees of visual angle. Four locations along the perimeter of each circle were marked with small square "dots," defining eight locations on the computer screen. Pilot testing indicated that these eight locations were sufficiently discriminable. Each visual stimulus was one of those eight dots, and all visual stimuli were white on a black background. All tasks were conducted inside a sound-attenuated shielded chamber in dim lighting.

Procedure

Working memory span tasks

All participants completed the working memory span tasks before the computerized *n*-back tasks. The working memory (WM) span tasks were completed in a well-lit lab room with the participant and the experimenter seated across a table from each other. Half of the participants completed the verbal WM span task first and the other half completed the visuospatial WM span task first. The two WM span tasks took approximately 10 minutes to complete total.

In the verbal WM span task, the examiner read sets of sentences to the participant at a normal reading pace, without pausing between the sentences. The participant's task was to listen to the sentences and remember the last word of each sentence in order. At the end of each set of sentences, the experimenter said, "recall," which cued the participant to repeat back the last word from each sentence in the order in which they were presented. The test began with a practice set of two sentences. If the participant successfully recalled the words in order, then the test progressed from sets of two to sets of three and so on until the participant failed to recall the last words of each sentence in order twice in a row. When both sets of sentences had been failed at a particular level, then the last successfully completed level was recorded as the participant's score.

The procedure for the visuospatial WM span task was very similar to that of the verbal WM span task. The Corsi apparatus was placed in the middle of the table between the experimenter and the participant. The experimenter tapped out each sequence, at a rate of approximately one block per second, using the eraser end of a pencil. The participant was then to repeat the sequence of blocks back to the examiner using either his or her index finger or the eraser end of another pencil, while remembering the last

block from each sequence. At the end of the set of sequences, the experimenter said, "recall," again cuing the participant to repeat back in order the last block from each sequence in the set. As in the verbal WM span task, this task began with a set of two sequences for practice. If the participant succeeded at repeating the last block from each sequence, then the test proceeded to sets of 3 and then to sets of 4 and so on, until two successive failures. The highest level completed successfully was recorded as the participant's score.

***N*-back tasks**

Participants completed 8 single-task and 4 dual-task blocks in a 2 x 2 x 4 (single/dual x audio/visual x *n*) repeated measures design. Each of the dual-task blocks yielded two measures, one for the visual task and one for the auditory task. All participants completed the single-task conditions before the dual-task conditions, and all participants completed the single-tasks beginning with the 0-back and progressing in numerical order through the 3-back. Half of the participants were randomly assigned to complete the visual single-tasks first and half were randomly assigned to complete the auditory single-tasks first. Additionally, half of the participants completed the dual-tasks in the order 0-back through 3-back, and half completed the dual-tasks in the reverse order (i.e., 3-back to 0-back), in order to balance the effects of practice and fatigue in the dual-tasks. In all conditions, both auditory and visual stimuli were presented, however, different instructions indicated whether the person should respond to the visual stimuli, the auditory stimuli, or both.

A block began with a visual fixation cross in the center of the computer monitor screen that lasted for 500 ms. At the end of this fixation period, one of the 8 dots appeared on the screen along with the fixation cross for 280 ms and was then replaced by

the fixation cross alone. There was a 2250 ms Visual-Auditory stimulus onset asynchrony (SOA) interval, at the end of which one of the 8 auditory consonants played over the headphones. This was followed by a 2250 Auditory-Visual SOA, which was followed by the next visual stimulus, beginning the next "trial." This cycle of visual stimulus followed by auditory stimulus continued for 80 stimuli of each type. At the end of each block, participants received feedback regarding their accuracy in terms of number and percentage of hits, false alarms, correct rejections, and misses, as well as an overall d' score. The experimenter gave a brief description of these different measures to each participant after the first block along with the feedback.

In the auditory-verbal *n*-back single-task conditions, the participants' task was to respond vocally into a microphone with "yes" to indicate that the current letter matched the letter *n* stimuli back in the series, where *n* represents 1, 2, and 3, in different blocks of trials, or "no" to indicate that the current letter did not match the letter *n* back in the series. In the "0-back" condition, the participants' task was to respond "yes" when the current letter matched a target letter that was presented prior to the start of the series, and "no" when the current letter did not match the target. The target remained constant for all 0-back single-task auditory blocks.

In the visual-spatial single-task conditions, the participants' task was to press the "f" key on the computer's keyboard to indicate "match" when the current stimulus was in the same spatial location within the visual display as the stimulus *n* back in the series, or to press the "j" key to indicate "nonmatch" when the current stimulus was not in the same spatial location as the stimulus *n* back. Similar to the auditory task, in the 0-back visual task, the participant was to press the "match" key when the current stimulus was in the

target location presented prior to the series of stimuli and the "nonmatch" key when the current stimulus was not in the target location. The target location remained constant for all 0-back single-task visual blocks. For both visual and auditory tasks, participants completed blocks of the single-tasks for each level of *n* until their d' score was 3.0 or greater or for 3 blocks, which ever occurred first. The block on which they received the highest accuracy score for each level of n was then entered into the data analysis, and other blocks were considered practice blocks.

In the dual-task conditions, participants were instructed to respond to both the visual stimuli and the auditory stimuli in the same manner as in the single-tasks. They were also instructed to perform both tasks to the best of their ability, giving accurate performance in both tasks top priority. The targets for the 0-back dual-task conditions were different from the targets in the 0-back single-task conditions.

In all conditions, the probability of a match was .50. Reaction time and accuracy were recorded and served as the dependent measures. Participants were instructed before each block of trials to respond as quickly as possible while still ensuring accuracy.

Results

Working Memory Span Tasks

The scores on the working memory span tasks ranged between 2 and 6. The mean score on the verbal working memory span task was 4.1 with a standard deviation of 0.78. The mean score on the visuospatial WM span task was 3.4 with a standard deviation of 1.04. The modal score for both tasks was 4. Correlations were computed between the verbal and visuospatial WM span tasks and between each of the WM span tasks and each of the single-task and dual-task accuracy and RT measures for all levels of *n*. Figure 1

shows the relationship between scores on the verbal and the visuospatial WM span tasks. The two WM span tasks were significantly correlated, $r = .45$, $p = .01$. The correlations between each of the WM span measures and accuracy on each level of the *n*-back are given in Table 1. None of the correlations between the WM span measures and RT on any of the levels of the *n*-back were significant, $.10 \leq p \leq .99$.

Table 1. Pearson Product Moment Correlations Between the Working Memory (WM) Span Tasks and the *n*-Back Tasks.

		Single-tasks							
		Visual *n*-back				Auditory *n*-back			
Verbal WM span		0	1	2	3	0	1	2	3
	r	-.04	.34	.26	.25	.08	.08	.16	.37*
	p	.85	.07	.17	.18	.68	.69	.40	.05
Visuospatial WM span									
	r	.13	.02	.33	.27	.00	.04	.37*	.46**
	p	.51	.92	.08	.15	1.00	.83	.04	.01

		Dual-tasks							
		Visual *n*-back				Auditory *n*-back			
Verbal WM span		0	1	2	3	0	1	2	3
	r	.03	-.35	-.17	-.13	.40*	-.25	.02	.03
	p	.88	.06	.37	.48	.03	.19	.92	.86
Visuospatial WM span									
	r	.45*	.06	.003	.13	.25	-.13	.17	.21
	p	.01	.76	.99	.49	.18	.50	.37	.27

Note: *Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.01 level.

***N*-back Tasks**

A 2 x 2 x 4 repeated measures analysis of variance was conducted on both the d' and reaction time data. An α-level of .05 was used for all ANOVAs. Figure 2 shows the mean accuracy for the visual and auditory single- and dual-tasks as a function of level of *n*. Participants were more accurate in the single-tasks than in the dual-tasks, $F(1, 29) = 72.89, p < .001$, and they were more accurate in the auditory-verbal tasks than in the visual-spatial tasks, $F(1, 29) = 28.81, p < .001$. There was a significant effect of level of *n*, with accuracy decreasing with increasing levels of *n*, $F(3, 87) = 141.95, p < .001$. There was a significant interaction between the single-dual factor and level of *n*, $F(3, 87) = 38.40, p < .001$. There was also a significant interaction between task modality (visual vs. auditory) and level of *n*, $F(3, 87) = 3.35, p = .02$, and the three-way interaction was significant $F(3, 87) = 8.11, p < .001$. Another way of visualizing the accuracy data is the Performance Operating Characteristic (POC) curves shown in Figure 3.

To investigate these effects further, specific pair-wise comparisons related to the hypotheses of the study were conducted. To control for multiple comparisons, a Bonferroni corrected α-level of .006 was used for all t-tests. For all levels of *n*, and for each task modality, the single-task performance was compared to the dual-task performance. For the 0-back tasks, there was a trend for accuracy for the visual dual-task to be higher than the visual single-task, and a trend for the accuracy for the auditory dual-task to be lower than the auditory single-task, but these trends did not reach significance, $t(29) = 2.61, p = .01$, and $t(29) = -2.258, p = .03$, respectively. For the 1-back tasks, accuracy on the visual single- and dual-tasks did not differ, $t(29) = -0.12, p = .91$, but there was a non-significant trend for accuracy on the auditory dual-task to be lower than on the single-task, $t(29) = -2.75, p = .01$. For the 2-back tasks, both the visual and

auditory dual-tasks showed a significant decline in accuracy over the single-tasks, $t(29) = -8.05$, $p = .001$, and $t(29) = -5.894$, $p < .001$, respectively. Similarly, the 3-back dual-tasks showed a decline in accuracy over the single-tasks for both the visual and auditory tasks, $t(29) = -9.29$, $p < .001$, and $t(29) = -7.92$, $p < .001$, respectively.

Figure 4 shows mean reaction time (RT) for the visual and auditory single- and dual-tasks as a function of level of *n*. In the RT analyses, responses to the single-tasks were faster than to the dual-tasks overall, $F(1, 29) = 13.31$, $p = .001$, and responses to the visual tasks were faster than to the auditory tasks, $F(1, 29) = 9.94$, $p = .004$. There was a significant effect of level of *n*, with RT increasing with increasing levels of *n*, $F(3, 87) = 59.91$, $p < .001$. The interaction between the single-dual factor and level of *n* was not significant, $F(3, 87) = 2.04$, $p = .12$, but both the single/dual factor x task modality interaction and the task modality x level of *n* interaction were significant, $F(1, 29) = 9.78$, $p = .004$, and $F(3,87) = 7.66$, $p < .001$, respectively. The three-way interaction was also significant, $F(3, 87) = 7.19$, $p < .001$.

Just as with the accuracy data, pair-wise comparisons related to the study's hypotheses were carried out on the RT data, and a Bonferroni corrected α-level of .006 was used for all *t*-tests. For the 0-back tasks, there was no difference in RT for the auditory single- versus dual-tasks, $t(29) = 0.73$, $p = .47$, but there was a non-significant trend for the dual-task responses to be slower than the single-task responses for the visual tasks, $t(29) = 2.67$, $p = .01$. For the 1-back tasks, there was no difference in RT for the visual tasks, $t(29) = .19$, $p = .85$, but the dual-task responses were slower than the single-task responses for the auditory tasks, $t(29) = 3.59$, $p = .001$. For the 2-back and 3-back tasks, there was no difference in RT for the visual single-tasks compared to the dual-

tasks, $t(29) = .95$, $p = .35$, and $t(29) = .03$, $p = .97$, respectively, but participants were slower to respond to the dual-tasks than to the single-tasks for the auditory tasks, $t(29) = 4.52$, $p < .001$, and $t(29) = 3.11$, $p = .004$, respectively.

Discussion

The main goal of this experiment was to demonstrate that the operation of the central executive is necessary in carrying out the 2- and 3-back tasks, but much less necessary in carrying out the 0- and 1-back tasks. The pattern of accuracy and RT results were largely consistent with this hypothesis. The POC curves for the accuracy data show this rather dramatically. Performance on the 0- and 1-back dual-tasks is nearly perfectly preserved as indicated by the almost 90° angle of those two POC curves. The curves for the 2- and 3-back indicate that performance in the dual-task situation suffers.

The 2- and 3- back tasks showed a marked decrease in accuracy between the single- and dual-task conditions for both the visual and auditory tasks. The visual 2- and 3-back tasks did not show a difference between the single- and dual-task conditions in RT, but the auditory 2- and 3-back tasks showed longer latency for the dual-task conditions than for the single-task conditions. Because these tasks did not utilize the same input or output modalities, nor did they utilize similar working memory "codes" (i.e., one was a verbal task and one was a spatial task), the interference seen in the 2- and 3-back tasks is most likely attributable to a need for central executive resources. This is consistent with Smith and Jonides' (1997) interpretation of an increase in DLPFC activation in the 2- and 3-back tasks as a need for executive processes in these tasks.

The 0-back and 1-back tasks did not show significant decreases in accuracy between the single- and dual-task conditions, although there was a trend for performance

on the auditory dual-tasks to be less accurate than the auditory single-tasks. The visual 0- and 1-back tasks did not show evidence of dual-task interference in the RT data, nor did the auditory 0-back task, however, the auditory 1-back did show a significant increase in RT for the dual-task condition compared to the single-task condition. This trend for the auditory 1-back to produce less accurate performance in the dual-task condition coupled with the significantly increased reaction time in the dual-task condition may be taken as evidence that the 1-back task does actually require central executive resources. Because performance of the visual 1-back was preserved in the dual-task condition, the pattern of results seen in the auditory 1-back may indicate a strategy of providing resources to the task perceived to be more difficult at the expense of decreased performance on the task perceived to be easier. Bourke, Duncan, and Nimmo-Smith (1996) have found evidence that regardless of which task is designated as primary in a dual-task situation, people tend to allocate more resources to the task they consider more demanding. The participants were overall less accurate on the visual tasks, and because they received feedback on their accuracy performance after each block, they were aware that they performed less well than on the auditory tasks. It is also possible that the participants subjectively perceived the spatial task to be more difficult independent of their accuracy scores because they may have less well-developed strategies in place for trying to remember where things are in space than for verbal materials. Given the need to allocate executive resources to the two 1-back tasks, the participants may have chosen, consciously or unconsciously, to dedicate more resources to the visual task, thus enabling preserved performance on the dual-task, and fewer resources to the auditory task, thus producing the small decrease in performance observed.

For the visual 0-back, there was a trend for accuracy to be better on the dual-task than the single-task. This is most likely due to practice and a ceiling effect. The 0-back is a rather simple task and accuracy was quite high even in the first block of the single-task. In fact, most people required only one block of the single-task to reach the criterion of a d' of 3 or higher. Because the visual 0-back was the first task in which the participants made a manual response, it may be that they required some number of trials to become accustomed to the response key mappings. This may have led to less than perfect performance on the single-task 0-back. Performance on the dual-task 0-back was very nearly perfect in all subjects perhaps because by the time they performed the dual-task blocks, they had had many blocks to practice the response key mappings. There was also a non-significant trend for slower RTs to the visual 0-back in the dual-task condition. The marginally slower RTs and the marginally less accurate responses in the visual 0-back dual-task may simply reflect a shifted speed-accuracy trade-off.

A secondary goal of this experiment was to consider the role of individual differences in working memory capacity in carrying out two demanding working memory tasks concurrently. To this end, participants completed two tests considered to measure working memory span in different domains: Daneman and Carpenter's (1980) Listening Span test and a modified version of the Corsi Block-tapping test. These two measures did correlate with each other moderately indicating that some domain-general resources may be necessary for the manipulation of information in the phonological loop as well as the visuospatial sketchpad. It would be reasonable, given Baddeley's (1986) model, to call these domain-general resources "executive processes." This conclusion is in accord with the findings of Bors and McLeod (1996) who reported that Daneman and

Carpenter's (1980) working memory span task correlates moderately with tests of problem-solving, abstract reasoning, and general intelligence, which are considered to tap executive functions to some degree. Because the modification of the Corsi Block-tapping task was designed to be an analog of Daneman and Carpenter's task and because it requires the maintenance and manipulation of information, it is reasonable to believe that this task also should tap executive processes.

Given the conclusion that these two working memory span tasks do test executive processes, it is surprising that individual performance on these tasks showed very few correlations with performance of the *n*-back tasks. Among the single-tasks the verbal WM span task correlated only with the auditory 3-back , and the visuospatial WM span task correlated only with the auditory 2- and 3-backs. These correlations do make sense in light of the conclusion that the 2- and 3-back tasks require executive processes, however why the visual 2- and 3-back single-tasks did not correlate with either of the WM span tasks is not clear.

It is also not clear why the only dual-task performance that correlated with the WM span tasks was the 0-back. This is a relatively easy task and performance did not show any interference when the auditory and visual 0-backs were paired. It is true that the verbal WM span task correlated with performance of the auditory 0-back in the dual-task situation, and the visuospatial WM span task correlated with performance of the visual 0-back in the dual-task situation, so it may be that this correlation is driven by domain-specific processes rather than domain-general processes. Why performance of the other dual-tasks, especially the 2-back and the 3-back which most clearly required executive resources, did not correlate with the WM span tasks is not easily explained.

One difficulty may be that the measurement of WM capacity with these tasks is not very fine grained. The standard scoring procedure does not permit "partial credit" if, for example, the participant gives all of the correct items but one is out of order. This procedure produces a whole number score that is in the range of 2 to 6. This may be the main reason that little variation was observed in the scores on the WM span tasks, and this may lead to low correlations with the experimental tasks. It is also possible that the lack of correlations between the WM span tasks and the n-back tasks may indicate that there is not one unitary central executive, but rather multiple dissociable processes. Perhaps the WM span tasks and the *n*-back tasks require qualitatively different executive processes for successful performance.

One potential alternative explanation of the general trends in the *n*-back data is that the 0-back and 1-back tasks actually do require similar executive processes, but because there was such a long stimulus onset asynchrony (SOA), perfect timesharing of the two tasks was possible. This would lead to no decrement in performance in the dual-task situation relative to the single-task situation, as was observed. In other words, it is possible in the 0- and 1-back tasks that by the time the auditory stimulus was presented, all of the executive processes required by the visual task (e.g., updating, temporal sequencing, response selection) had already been completed. This possibility was explored in Experiment 2.

Figures

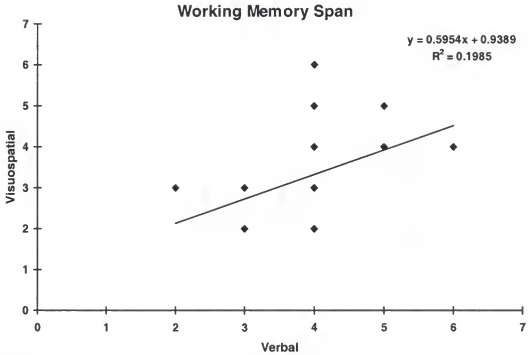

Figure 1. The relationship between verbal WM span and visuospatial WM span.

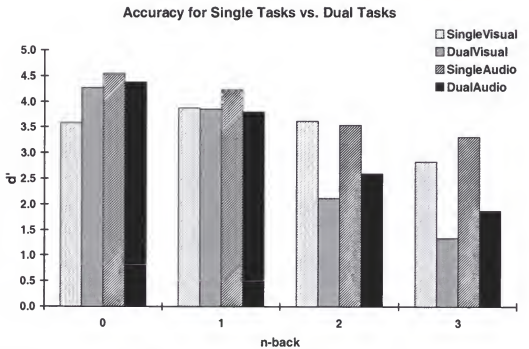

Figure 2. Accuracy on the auditory and visual single- and dual-task conditions.

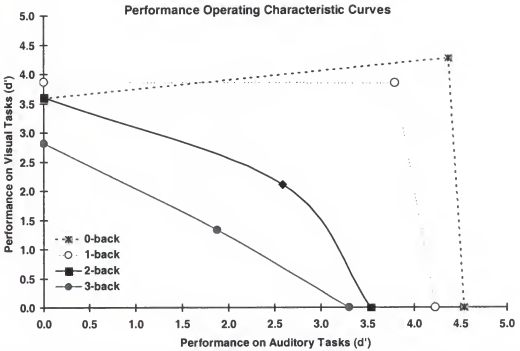

Figure 3. Performance Operating Characteristic curves for accuracy on the auditory tasks as a function of accuracy on the visual tasks.

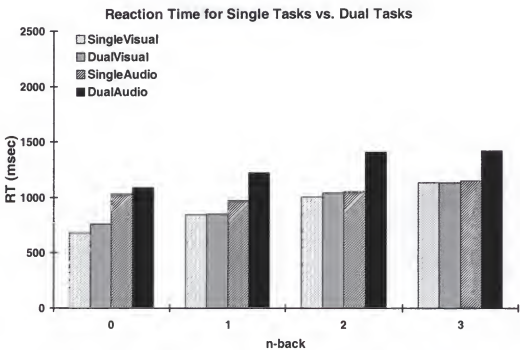

Figure 4. Reaction time (RT) for the visual and auditory single- and dual-task conditions.

CHAPTER 3
EXPERIMENT TWO

Experiment 1 presented data that suggested that the 2- and 3-back tasks require executive resources, the 1-back may require some executive resources, and the 0-back appears to require no executive resources. An alternative to the resource explanation for dual-task performance is the central bottleneck account best articulated by Pashler (1998). This account of dual-task performance posits that perceptual processing and response execution may proceed in parallel but that "central processing" such as response selection must proceed in serial.

The classic demonstration of this central bottleneck is seen in the results of psychological refractory period (PRP) experiments. In each trial of a PRP experiment, the participant is presented with two stimuli (S1 and S2) and makes two speeded responses (R1 and R2). The duration between the onset of the first stimulus and the onset of the second stimulus (the stimulus onset asynchrony, SOA) is varied and its effect on reaction time to the first stimulus (RT1) and to the second stimulus (RT2) is measured. The general finding is that with shorter SOAs, RT2 increases linearly with decreases in SOA (Pashler, 1994). This increase in RT2 is generally interpreted as evidence for a central bottleneck.

From this viewpoint, it may be that the 0-back and the 1-back tasks did not show any or very much interference when the verbal and the spatial tasks were combined in experiment 1 not because they do not require the same mechanisms, but rather because

the central processing stage of the first task had already been completed when the stimulus of the second task was presented. In other words, the central processing stages of these two tasks did not overlap in time and thus there was no delay in processing the second stimulus. This hypothesis was tested in the present experiment by shortening the SOA between the visual and the auditory stimulus. If the 0- and the 1-back rely on the same central mechanism as the 2- and the 3-back, then the reaction times to the auditory (2^{nd}) stimuli should be slowed in the dual-task conditions regardless of level of *n*.

The WM span tasks were also administered in the second experiment to continue the investigation of individual differences in the ability to coordinate two difficult working memory tasks. It was hypothesized that the change in the visual to auditory stimulus SOA may significantly change the nature of the dual-task conditions and thus may be better correlated with performance on the WM span tasks.

Method

Participants

Thirty-seven undergraduates (8 male) at the University of Florida participated in partial fulfillment of a course requirement. Participants' ages ranged from 18 to 30 (M = 20, SD = 3.3) years. All had normal or corrected-to-normal vision and normal hearing.

Materials and Apparatus

The materials and apparatus were the same as in experiment 1.

Procedure

All of the procedures were identical to experiment 1 with the following exception: the timing of the stimuli was altered to incorporate the shorter SOA between the first (visual) and second (auditory) stimulus. A block began with just a visual fixation cross

on the computer monitor that lasted for 500 ms. At the end of this fixation period, one of the 8 dots appeared on the screen along with the fixation cross for 280 ms and was then replaced by the fixation cross alone. There was a 380 ms Visual-Auditory SOA, at the end of which one of the 8 auditory consonants played over the headphones. This was followed by a 4120 ms Auditory-Visual SOA, which was followed by the next visual stimulus, beginning the next "trial." In this manner the length of a "trial" (one visual stimulus and one auditory stimulus) was the same as in experiment 1, and the rate of presenting the stimuli was the same as in experiment 1. All that varied from experiment 1 to experiment 2 was the length of time between the presentation of the visual stimulus and the presentation of the auditory stimulus.

Results

Working Memory Span Tasks

The scores on the verbal working memory span task ranged between 2 and 6. The scores on the visuospatial working memory span task ranged between 0 and 6. The mean score on the verbal working memory span task was 4.1 with a standard deviation of 0.85. The mean score on the visuospatial WM span task was 3.5 with a standard deviation of 1.15. The modal score for both tasks was 4. Correlations were computed between the verbal and visuospatial WM span tasks and between each of the WM span tasks and each of the single-task and dual-task accuracy and RT measures for all levels of *n*. Figure 5 shows the relationship between scores on the verbal and the visuospatial WM span tasks. The two WM span tasks were not significantly correlated, $r = -.06$, $p = .73$. The correlations between each of the WM span measures and accuracy on each level of the *n*-

back are given in Table 2. The correlations between each of the WM span measures and reaction time on each level of the *n*-back are given in Table 3.

Table 2. Pearson Product Moment Correlations Between the Working Memory (WM) Span Tasks and Accuracy (d') for the *n*-Back Tasks.

		Single-tasks							
		Visual *n*-back				Auditory *n*-back			
Verbal WM span		0	1	2	3	0	1	2	3
	r	.01	.001	-.02	.22	-.15	.09	-.11	.04
	p	.94	.995	.93	.20	.37	.61	.52	.84
Visuospatial WM span									
	r	.07	.09	.12	-.09	.14	-.11	.42**	.14
	p	.70	.60	.48	.60	.41	.52	.01	.43

		Dual-tasks							
		Visual *n*-back				Auditory *n*-back			
Verbal WM span		0	1	2	3	0	1	2	3
	r	-.08	-.21	.16	.33*	-.04	-.08	.16	.17
	p	.64	.21	.34	.05	.80	.66	.34	.32
Visuospatial WM span									
	r	.02	.06	-.04	.19	-.03	-.01	-.001	.11
	p	.93	.72	.82	.27	.86	.97	.995	.51

Note: *Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.01 level.

Table 3. Pearson Product Moment Correlations Between the Working Memory (WM) Span Tasks and Reaction Time for the *n*-Back Tasks.

		Single-tasks							
		Visual *n*-back				Auditory *n*-back			
Verbal WM span		0	1	2	3	0	1	2	3
	r	.01	.001	-.02	.22	-.15	.09	-.11	.04
	p	.94	.995	.93	.20	.37	.61	.52	.84
Visuospatial WM span									
	r	.07	.09	.12	-.09	.14	-.11	.42**	.14
	p	.70	.60	.48	.60	.41	.52	.01	.43

		Dual-tasks							
		Visual *n*-back				Auditory *n*-back			
Verbal WM span		0	1	2	3	0	1	2	3
	r	-.08	-.21	.16	.33*	-.04	-.08	.16	.17
	p	.64	.21	.34	.05	.80	.66	.34	.32
Visuospatial WM span									
	r	.02	.06	-.04	.19	-.03	-.01	-.001	.11
	p	.93	.72	.82	.27	.86	.97	.995	.51

Note: *Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.01 level.

_N_-back Tasks

A 2 x 2 x 4 repeated measures analysis of variance was conducted on both the d' and reaction time data. An α-level of .05 was used for all ANOVAs. Figure 6 shows the mean accuracy for the visual and auditory single- and dual-tasks as a function of level of *n*. Participants were more accurate in the single-tasks than in the dual-tasks, $F(1, 36) = 154.87$, $p < .001$, and they were more accurate in the auditory-verbal tasks than in the visual-spatial tasks, $F(1, 36) = 19.84$, $p < .001$. There was a significant effect of level of *n*, with accuracy decreasing with increasing levels of *n*, $F(3, 108) = 128.42$, $p < .001$. There was a significant interaction between the single-dual factor and level of *n*, $F(3, 108) = 26.38$, $p < .001$. There was also a significant interaction between task modality (visual vs. auditory) and level of *n*, $F(3, 108) = 3.79$, $p = .01$. The three-way interaction was not significant $F(3, 108) = 0.51$, $p = .68$. Another way of visualizing the accuracy data is the Performance Operating Characteristic (POC) curves shown in Figure 7.

To investigate these effects further, specific pair-wise comparisons related to the hypotheses of the study were conducted. To control for multiple comparisons, a Bonferroni corrected α-level of .006 was used for all *t*-tests. For all levels of *n*, and for each task modality, the single-task performance was compared to the dual-task performance. For the 0-back tasks, there was a trend for accuracy for the visual dual-task to be lower than the visual single-task, and a trend for the accuracy for the auditory dual-task to be lower than the auditory single-task, but these trends did not reach significance, $t(36) = -2.26$, $p = .03$, and $t(36) = -2.01$, $p = .05$, respectively. For the 1-back tasks, there was also a non-significant trend for accuracy on the visual and auditory single-tasks and to be lower than the dual-tasks, $t(36) = -1.77$, $p = .09$, and $t(36) = -2.02$, $p = .05$, respectively. For the 2-back tasks, both the visual and auditory dual-tasks showed a

significant decline in accuracy over the single-tasks, $t(36) = -8.06$, $p < .001$, and $t(36) = -6.49$, $p < .001$, respectively. Similarly, the 3-back dual-tasks showed a decline in accuracy over the single-tasks for both the visual and auditory tasks, $t(36) = -7.81$, $p < .001$, and $t(36) = -9.83$, $p < .001$, respectively.

Figure 8 shows mean reaction time (RT) for the visual and auditory single- and dual-tasks as a function of level of *n*. In the RT analyses, responses to the single-tasks were faster than to the dual-tasks overall, $F(1, 36) = 267.70$, $p < .001$, and responses to the auditory tasks were faster than to the visual tasks, $F(1, 36) = 95.24$, $p < .001$. There was a significant effect of level of *n*, with slower RTs with increasing levels of *n*, $F(3, 108) = 108.75$, $p < .001$. There was a significant interaction between the single/dual factor and level of *n*, $F(3, 108) = 3.49$, $p = .02$, and both the single/dual factor x task modality interaction and the task modality x level of *n* interaction were significant, $F(1, 36) = 48.37$, $p < .001$, and $F(3, 108) = 41.87$, $p < .001$, respectively. The three-way interaction was marginally non-significant, $F(3, 108) = 2.58$, $p = .06$.

Just as with the accuracy data, pair-wise comparisons related to the study's hypotheses were carried out on the RT data, and a Bonferroni corrected α-level of .006 was used for all *t*-tests. For both the auditory and visual tasks for each level of *n*, t-tests were conducted comparing the single-task RT with the dual-task RT. All of these pair-wise comparisons were significant as shown in Table 4.

Table 4. Dual-task – Single-task Paired Comparisons of Reaction Time for the Auditory and Visual Tasks for Each Level of *n*.

n-back	Comparison	Mean Difference	*SD*	df	*t*	*p*
0	Dual Visual – Single Visual	803.08	390.18	36	12.18	<.001
	Dual Auditory – Single Auditory	199.71	264.22	36	4.47	<.001
1	Dual Visual – Single Visual	717.05	367.60	36	11.54	<.001
	Dual Auditory – Single Auditory	272.90	270.16	36	6.00	<.001
2	Dual Visual – Single Visual	885.23	401.08	36	13.06	<.001
	Dual Auditory – Single Auditory	346.84	327.97	36	6.26	<.001
3	Dual Visual – Single Visual	737.45	449.59	36	9.70	<.001
	Dual Auditory – Single Auditory	314.62	308.57	36	6.03	<.001

Discussion

One of the aims of this study was to further investigate the nature of individual differences in the coordination of two working memory tasks. Unlike the results of experiment 1, these data show no correlation between the verbal WM span test and the visuospatial WM span test. In experiment 1 it was concluded that the correlation between the two WM span tests may indicate that the tasks share some common processes, the most likely being executive processes. Reasoning along those same lines would lead to the conclusion that the lack of a correlation between the two WM span tests in experiment 2 indicates that these tests do not require any common resources, including executive resources. These two conclusions are difficult to reconcile. It seems unlikely that sampling error could entirely account for the large difference in correlations in the

two experiments (.446 in experiment 1 and -.058 in experiment 2), although it surely contributes to the discrepancy.

Just as in experiment 1, neither of the WM span tasks correlate with performance of very many of the *n*-back tasks and no real coherent pattern of correlations emerges. It appears that these tests do not capture the relevant individual differences for performance of either the auditory-verbal or the visual-spatial *n*-back. This is surprising because Daneman and Carpenter's (1980) Listening span task certainly appears to require the phonological loop for storage of information and the central executive for the manipulation of verbal information. Even if neither the verbal WM span test nor the auditory-verbal *n*-backs require executive resources, one would expect that individual differences in the capacity of the phonological loop alone would produce significant correlations between the verbal WM span test and the verbal *n*-backs. Likewise, the modified Corsi Block-tapping test has a certain amount of face validity as a test of visuospatial working memory. A number of studies have made use of the original Corsi Block-tapping task and its interpretation as a measure of visuospatial memory appears to have been well validated (Berch, Krikorian, Huha, 1998), thus even in the absence of the need for executive processes, one would expect this task to correlate with the visual-spatial *n*-backs due to its apparent reliance on spatial resources.

Again, the argument can be made that the scoring procedures for the two tasks produce measurements that are too coarse. It may be that modifying how the tests are scored may produce a more varied sample. For example, a procedure of allowing partial credit for performance that is not perfect but that is not far from the correct answer could be an improvement. Other useful modifications might be to randomize the presentation

of set length, instead of always building up, and to provide more than two trials per set length. Making these modifications and then scoring the percent of all items that were successfully completed might be a better measure of individual differences in these two domains, and thus might correlate better with the different versions of the *n*-back.

The main purpose of this second experiment, though, was to examine the possibility that the lack of interference seen in the 0- and 1-back dual-tasks may have actually reflected perfect timesharing of the two tasks rather than the idea that these tasks do not require the same executive resources, as do the 2- and the 3-back.

The accuracy data are a clear replication of the accuracy data of experiment 1. There is little or no decrement in the dual-task situations for the 0- and 1-backs, but there is a marked decline in performance for the 2- and 3-back tasks, as evidenced by the significant interaction between the dual/single factor and the level of *n*, and further supported by the paired *t*-tests. The POC curves illustrate this clearly. The lines for the 0- and 1-back indicate preserved performance in the 0- and 1-backs, but the lines for the 2- and 3-back indicate a decline in performance on both the auditory and visual *n*-backs. Considered alone, the accuracy data would lead to the conclusion that executive resources are required for the 2- and 3-back tasks, but not for the 0- and 1-back tasks.

The reaction time data, however, indicate support for the view that there are some shared processes even in the 0- and 1-backs. Reaction time is slowed in all dual-task conditions regardless of level of *n*. The patterns apparent in Figure 4 and the significant interaction between the single/dual factor and task modality indicate that the dual-task slowing was even more pronounced in the visual tasks than in the auditory tasks. Further, the shorter reaction times to the auditory stimuli in the dual-task condition than

to the visual stimuli in the dual-task conditions indicates that the participants were responding to the auditory stimulus before the visual stimulus, on average. This is interesting because the visual stimulus was actually presented before the auditory stimulus. It is as though the participants buffered the visual stimulus, made their response to the auditory stimulus and then turned their attention back to the visual stimulus. This strategy seems counterintuitive and not a terribly efficient way to do the task. This strategy may again reflect the participants' perception that the visual task was the more challenging task. Informal debriefing of the participants indicates support for this notion. Many participants indicated that the visuospatial task was more difficult than the verbal task and most indicated an inability to verbalize any strategy that they used to complete the task. Accuracy was lower in the visual tasks overall, and the participants did receive feedback on their accuracy, thereby reinforcing the perception that the visual task was more difficult. It may be that the SOA was so short that the stimuli arrived very nearly simultaneously to the perception of the participants, and therefore having essentially two stimuli to process at once, the participants decided to perform what they perceived to be the easier task first to "get it out of the way" so that they would then be able to give their full attention to the more difficult task.

The reaction time data provide further support for the views of Pashler (1998) and others who support central bottleneck theories. Even in the 0-back tasks, which are rather simple target detection tasks, there appear to be some processes that must be performed in serial. Pashler suggests that response selection is one process that occupies the single central channel that produces the bottleneck in PRP-type tasks. Clearly both the auditory and the visual versions of the *n*-back require responses to be selected, and this may be the

source of the interference observed in the RT data in this second experiment. In addition, Carrier and Pashler (1995) have found evidence that memory retrieval also occupies the single central channel, and therefore may be an additional source of interference in dual-task situations. Even the 0- and the 1-back require some memory retrieval, although it is minimal compared to the demands of the 2- and 3-back. The lesser demands on memory retrieval in the 0- and 1-back may account for the lack of interference observed in the accuracy data and the lesser interference observed in the reaction time data. Taken together, the accuracy and reaction time data in this second experiment points to the conclusion that there are probably many executive functions and thus it is unlikely that there exists a unitary central executive capable of carrying out these disparate tasks.

Figures

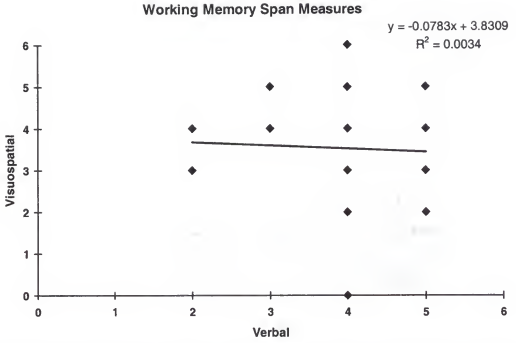

Figure 5. The relationship between verbal and visuospatial working memory span.

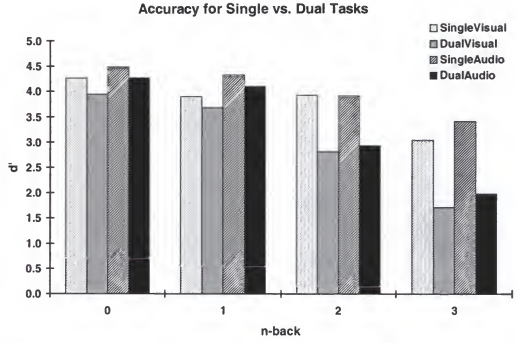

Figure 6. Accuracy (d') for auditory and visual tasks in the single- versus dual-task conditions.

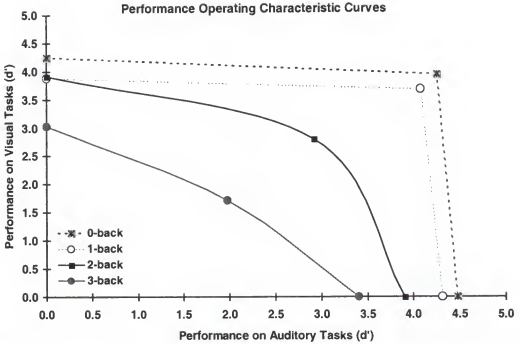

Figure 7. Performance Operating Characteristic (POC) curves for each level of *n*.

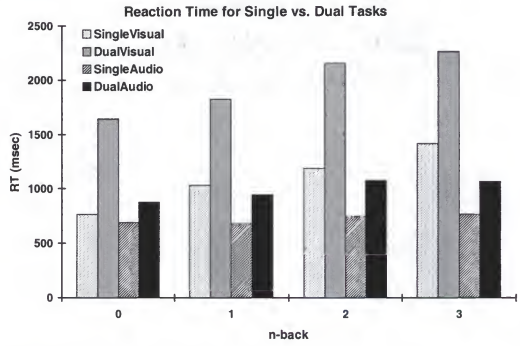

Figure 8. Reaction time for the auditory and visual single- and dual-task conditions for each level of *n*.

CHAPTER 4
EXPERIMENT THREE

In both experiments 1 and 2, the pattern of results indicated that two 0-back tasks and two 1-back tasks could be performed concurrently without a decrement in accuracy, but that performing two 2-back or two 3-back tasks concurrently produced a decline in accuracy. This pattern was consistent when stimuli were presented with a long SOA and with a short SOA. Because the two *n*-back tasks that were paired in these experiments used different input modalities, different output modalities, and different working memory codes, it was suggested that the only processes that could compete with each other in the dual-task conditions would be the so-called executive processes. This interpretation of the experimental design and resulting data is consistent with a multiple resource model of attention.

Unitary resource models, however, would predict the same pattern of results simply due to task difficulty. It could be argued that the 1-back is such a simple task, that is, requires so few attentional resources that no dual-task situation will produce a decrement in accuracy regardless of the nature of the secondary task. Likewise, the 3-back is such a demanding task that perhaps any secondary task would produce a decrease in accuracy. In other words, it is not necessary to posit qualitatively different resources, such as phonological, visuospatial, and executive resources, in order to explain the accuracy data of experiments 1 and 2. One undifferentiated pool of resources could be responsible for the decrements observed and not observed for the various levels of *n*.

The current experiment was designed to test this possibility. The dual-task paradigm was again utilized, but this time the auditory-verbal 1-back (hypothesized to require little or no executive resources) and 3-back (hypothesized to require executive resources) were paired with three different tasks designed to tax different aspects of working memory, according to Baddeley's (1986) model.

A rhyme judgment task in which participants were asked to decide if pairs of visually presented words rhymed or not was constructed in order to occupy the resources of the phonological loop. It has been shown that visually presented words are recoded into their phonological constituents when participants are asked to remember or manipulate them (Logie, 1995). The task parameters were designed so that the stimuli would remain on the screen until the participant made a response and thus there would be little need for the participant to try to hold these words in working memory while making a decision, however, despite its minimal working memory requirements, it was expected that this phonological task would interfere with the auditory-verbal *n*-back regardless of level of *n* due to both tasks' reliance on phonological resources.

A mental rotation task, based on that used by Shepard and Metzler (1971), in which participants were asked to judge whether two figures were identical or mirror images of each other, was utilized in order to occupy the visuospatial sketchpad. It has been reliably found that mental rotation tasks are interfered with by other spatial tasks such as alternate spatial tapping (Logie, 1995), and thus likely rely on the visuospatial sketchpad to some degree. Just as in the rhyming task, the mental rotation task was designed so that the stimuli would be available on the screen until the participant made his or her response, and thus there would be little need to hold the images in working

memory while a decision was made. Because the auditory-verbal *n*-back is not expected to rely on visuospatial resources, and the mental rotation task is not expected to rely on phonological resources, little interference would be expected at any level of *n* according to a multiple resources view.

The third task was a random keypress generation (RKG) task. In this task the participant is instructed to produce a series of responses with the requirement that the resulting overall series be as random as possible. The random generation paradigm has been used in studies of a range of tasks, including choosing moves in chess and learning artificial grammars, and a range of human populations, including Alzheimer's and Korsakoff's patients (Baddeley, Emslie, Kolodny, & Duncan, 1998). The overall conclusion of studies using this paradigm is that this task relies on the central executive component of working memory. If the results of experiments 1 and 2 were due to the operation of the central executive in the 2- and 3-backs, but not in the 0- and 1-backs, then it would be expected that the RKG task would also produce this same pattern of results as in those experiments. That is, the RKG task was expected to interfere with the 3-back task but not with the 1-back task.

Method

Participants

Twenty-nine undergraduates (14 male) at the University of Florida participated in partial fulfillment of a course requirement. Participants' ages ranged from 18 to 31 (M = 20, SD = 2.4) years. All had normal or corrected-to-normal vision and normal hearing.

Materials and Apparatus

An IBM-compatible Pentium computer in a Windows environment presented all stimuli and recorded all responses. All tasks were conducted inside a sound-attenuated shielded chamber in dim lighting. The stimuli for the auditory *n*-back were the same as in experiments 1 and 2.

All visual displays were presented on a 17-inch computer monitor and all visual stimuli were white on a black background. The stimuli for the rhyme judgment task consisted of 200 pairs of words in four equal-sized categories: a) word pairs that rhymed but did not share the last three letters (e.g., flower-sour), b) word pairs that rhymed and did share the last three letters (e.g., food-mood, c) word pairs that shared the last three letters but did not rhyme (bread-plead), and d) words that were semantically associated but did not rhyme or share the last three letters (e.g., time-clock). In this manner, half of the word pairs rhymed and half did not, but the judgment could not be based on orthographic cues alone, and therefore required some kind of phonological representation. The semantic associates were drawn from the Interactive Associative Thesaurus (available online at http://www.itd.clrc.ac.uk/Activity/Psych+267) and rhyme words were drawn from the Lexical Freenet (available online at http://www.lexfn.com/).

The stimuli for the mental rotation task consisted of 6 non-verbalizable 2-dimensional block figures which could be paired with either the identical figure rotated some number of degrees (0˚, 90˚, 180˚, 270˚) or the mirror image of the figure rotated some number of degrees (0˚, 90˚, 180˚, 270˚). These combinations produced 168 unique pairs of stimuli.

The stimuli for the RKG task consisted of 8 small white dots similar to the dots used to mark the spatial locations in the visual-spatial *n*-back tasks of experiments 1 and

2. These dots were arranged equidistant from each other along the perimeter of an invisible circle that subtended 2 degrees of visual angle surrounding the fixation cross. Each dot was one stimulus and served merely as a visual metronome to help participants generate keypresses at the appropriate rate.

Procedure

The order of task completion was counterbalanced across participants, with the restriction that all single-tasks were completed before all dual-tasks. As in experiments 1 and 2, in the single-task conditions, both visual and auditory stimuli were presented and differential instructions indicated to which stimuli the participant should respond on any given block.

For blocks in which the *n*-back tasks were paired with the rhyme judgment task or the mental rotation task, a block began with a visual fixation cross which lasted 500 ms. At the end of this fixation period, a pair of visual stimuli (either pairs of words or pairs of figures depending on the block) were presented, one stimulus above the fixation cross and one below the fixation cross. These stimuli remained on the screen until the participant made a response or 2250 ms, which ever came first, and were then replaced by the fixation cross alone. There was a 2250 ms Visual-Auditory SOA, at the end of which one of the 8 auditory consonants played over the headphones. There was a 2250 Auditory-Visual SOA, which was followed by the next visual stimulus, beginning the next "trial." This cycle of visual stimulus followed by auditory stimulus continued for 80 stimuli of each type. At the end of each block, participants received feedback regarding their accuracy in terms of number and percentage of hits, false alarms, correct rejections, and misses, as well as an overall d' score. The experimenter gave a brief description of these different measures to each participant after the first block along with the feedback.

For blocks in which the *n*-back tasks were paired with the RKG task, a block began with a visual fixation cross which lasted 500 ms. At the end of the fixation interval, the stimuli for the RKG task then began appearing at the rate of one stimulus per second. After the RKG task had been underway for 2250 ms, the first auditory *n*-back stimulus was presented. One auditory stimulus was presented every 4500 ms thereafter until 80 auditory stimuli had been presented. This resulted in approximately 360 keypresses in the RKG task per block. At the end of each block, participants received feedback regarding their accuracy on the *n*-back task in terms of number and percentage of hits, false alarms, correct rejections, and misses, as well as an overall d' score, and they received a redundancy score for the RKG task. The experimenter gave a brief description of these different measures to each participant after the first block along with the feedback.

In the auditory-verbal *n*-back single-task conditions, the participants' task was to respond vocally into a microphone with "yes" to indicate that the current letter matched the letter *n* stimuli back in the series, where *n* represents 1 or 3, in different blocks of trials, or "no" to indicate that the current letter did not match the letter *n* back in the series. In the rhyme single-task condition, the participants' task was to press the "f" key on the computer's keyboard to indicate that the pair of words rhymed or to press the "j" key to indicate that the words did not rhyme. In the mental rotation single-task condition, the participants' task was to press the "f" key on the computer's keyboard to indicate that the pair of stimuli were the "same" or to press the "j" key to indicate that the were "mirror images." For the *n*-backs, rhyme, and mental rotation tasks, participants completed blocks of the single-tasks for each level of *n* until their d' score was 3.0 or

greater or for 2 blocks, which ever occurred first. The block on which they received the highest accuracy score was then entered into the data analysis, and other blocks were considered practice blocks.

In the RKG task, participants were instructed to produce a random series of keypresses using the 8 keys on the keyboard that constitute the "home row" keys (i.e., a, s, d, f, j, k, l, ;) at the rate of one keypress per second. They were instructed that the visual stimuli on the computer screen were to aid them in keeping an appropriate pace of generating responses, but otherwise were irrelevant to the task. Because instruction regarding what constitutes "random" is an important part of this task, the verbatim instructions given to the participants is reproduced in the Appendix. Participants performed one block of the RKG task for practice and one block that was entered into the analyses.

In the dual-task conditions, participants were instructed to respond to both the visual stimuli and the auditory stimuli in the same manner as in the single-tasks. They were also instructed to perform both tasks to the best of their ability, giving accurate performance in both tasks top priority.

In all of the *n*-back tasks, the probability of a match was .50. In the rhyme judgment tasks the probability of a rhyme pair was .50, and in the mental rotation task, the probability of an identical pair was .50. Accuracy (d') was the dependent measure in the n-back, rhyme, and mental rotation tasks, and redundancy (RND) was the dependent measure in the RKG task. After Teasdale, et al. (1995) and Marsh and Hicks (1998), RND was calculated using the following formula:

$$RND = \frac{\sum f_{ij} \cdot (\log f_{ij})}{\sum f_i \cdot (\log f_i)}$$

In this formula, i and j refer to rows and columns of an 8 X 8 frequency matrix of keypresses (rows) that follow other keypresses (columns), with f_i indicating the total frequency of response i and f_{ij} indicating the number of bigram responses where digit i follows digit j. This formula produces a number between 0 and 1 in which smaller numbers represent less redundancy, and thus a better random series. Richard Marsh of the University of Georgia graciously provided the Pascal code that calculated RND in this experiment.

Results

Three separate omnibus repeated measures ANOVAs were conducted on the accuracy data resulting from this experiment. The data from the auditory working memory tasks were entered into a 2 (level of n: 1-back vs. 3-back) X 4 (single, dual w/ rhyme, dual w/ RKG, dual w/ mental rotation) ANOVA. The data from the visual tasks was entered into two separate ANOVAs because the RKG task utilized a different dependent measure that is difficult to compare with accuracy as measured by d'. The data from the rhyme task and the mental rotation task were entered into a 2 (visual task: rhyme vs. rotation) X 3 (single, dual w/ 1-back, dual w/ 3-back) ANOVA, and the data from the RKG task were entered into a univariate repeated measures ANOVA with 3 levels (single, dual w/ 1-back, dual w/ 3-back). An α-level of .05 was used for all ANOVAs.

Figure 9 shows accuracy for the auditory working memory n-back tasks as a function of level of duality (single, dual w/ rhyme, dual w/ RKG, dual w/ mental rotation). In these tasks, the level of n significantly affected accuracy, $F(1, 28) = 118.050$, $p < .001$, with lower accuracy in the 3-back than the 1-back. There was also an effect of

level of duality, $F(3, 84) = 22.261$, $p < .001$, and an interaction between duality and level of n $F(3, 84) = 17.426$, $p < .001$.

To further explore these effects, specific paired comparisons were conducted related to the hypotheses of the study. To control for multiple comparisons, a Bonferroni corrected α-level of .008 was used for all t-tests. For both levels of n, the single-task performance was compared to dual-task performance for each of the three visual tasks. For the 1-back task, accuracy was significantly higher in the dual-task condition when the secondary task was the rhyme judgment task than it was in the single-task condition, $t(28) = 3.256$, $p = .003$. Performance of the 1-back task was significantly lower in the mental rotation dual-task condition than it was in the single-task condition, $t(28) = -4.902$, $p < .001$, and there was no significant difference between the single-task condition and the RKG dual-task condition $t(28) = 1.055$, $p = .301$. For the 3-back task, accuracy was not significantly lower in the rhyme judgment dual-task condition than it was in the single-task condition, $t(28) = -1.982$, $p = .057$, nor was it lower in the RKG dual-task condition, $t(28) = -1.897$, $p < .068$. There was, however, a significant decline in accuracy from the single-task condition to the mental rotation dual-task condition $t(28) = -3.409$, $p = .002$.

Figure 10 shows accuracy for the rhyme and mental rotation tasks as a function of level of duality (single, dual w/ 1-back, dual w/ 3-back). Performance was higher overall on the rhyme task than on the mental rotation task regardless of duality, $F(1, 28) = 96.809$, $p < .001$. There was also an effect of duality, $F(2,56) = 7.567$, $p = .001$, but the interaction between the two factors was not significant, $F(2, 56) = 1.041$, $p = .360$.

Paired comparisons were also conducted for the rhyme and mental rotation tasks comparing the single-task conditions with the dual 1-back condition and with the dual 3-back condition. Accuracy on the rhyme task did not differ from the single-task condition to the dual 1-back condition, $t(28) = -1.193$, $p = .243$, but performance did decline in the dual 3-back condition compared to the single-task condition, $t(28) = -3.374$, $p = .002$. A similar pattern arose in the mental rotation task. Performance of the mental rotation task did not differ between the single-task condition and the dual 1-back condition, $t(28) = 0.271$, $p = .788$. There was a trend for performance in the dual 3-back condition to be less accurate than in the single-task condition, but this trend failed to reach significance, $t(28) = -2.071$, $p = .048$.

Figure 11 shows the redundancy scores for the RKG task as a function of duality. The effect of duality was not significant, $F(2, 56) = 1.690$, $p = .194$, indicating that participants did not produce significantly more redundant (i.e., less random) series of responses for either of the dual-task conditions relative to the single-task condition.

Figures 12, 13, and 14 show the POC curves for the rhyme judgment, mental rotation, and random keypress generation tasks respectively. These figures make the relationships between performance on these many tasks clearer, and strategic tradeoffs between the two tasks in the dual-task conditions are easier to detect when the data are presented in this manner. It is important to keep in mind when examining Figure 14, however, that unlike the case with d' and other accuracy measures, an increase in the RND measure indicates a decrease in the quality of performance.

Discussion

The main purpose of this experiment was to examine the argument that the pattern of accuracy results seen in experiments 1 and 2 could be explained within a unitary resource model as merely reflecting the greater difficulty of the 2- and 3-back tasks rather than a need for executive processes specifically. Based on a multiple resources view, it was hypothesized that in this experiment a clear pattern would emerge in which both the 1-back and the 3-back showed interference with the rhyme generation task, the 1-back would show no interference with the RKG task but the 3-back would, and neither *n*-back task would show interference with the mental rotation task. The pattern of data is not that clear, however.

In examining the POC curves for the rhyme judgment tasks, it is clear that this task interfered with the 3-back task, but not with the 1-back task. In fact, performance on the 1-back task improved significantly in the dual-task situation while performance on the rhyme judgment task was preserved. This would indicate either that the 3-back and the rhyme task share resources as the 1-back and the rhyme task do not, or perhaps the argument of "mere difficulty" is valid. It seems unlikely that the 1-back task does not at all tax the phonological loop because the best strategy for successful performance of this task is verbal rehearsal of the current letter until the next letter is presented. The better explanation for this pattern of results, then, seems that the 1-back does not tax the phonological loop enough to cause significant problems for performing another phonological task concurrently, or in the parlance of unitary resource theories, it requires so few attentional resources that there are enough residual resources to enable preserved performance of the rhyme judgment task. It appears from these data that the 1-back is merely an easy task.

On the other hand, the POC curves for the mental rotation task show a decrement in performance of both the 1-back and the 3-back with preserved performance on the mental rotation task in the dual-task situations. There was a trend toward reduced accuracy on the mental rotation task when it was combined with the 3-back, but this trend did not reach significance. This decrement in the auditory tasks in the face of preserved performance of the visual tasks may again reflect the strategy noted by Bourke, Duncan, and Nimmo-Smith (1996) in which people tend to allocate more attention or effort to the task they consider more demanding at the expense of the task they consider easier. The mental rotation task clearly appears to be the more demanding task when one considers overall accuracy on this task as compared to the *n*-back tasks. It could even be argued, as was argued regarding the visual-spatial *n*-back of experiments 1 and 2, that even in the absence of this overt feedback regarding performance that participants may have subjectively considered the mental rotation task to be more challenging simply due to their having less practiced strategies for doing these tasks.

If the mental rotation task required visuospatial resources, and there was little demand to hold the images in working memory, then the question remains why the task interfered with the auditory-verbal *n*-backs at all. From a multiple resources perspective, these two tasks should not require the same resources and thus should not interfere with each other. One explanation would be the argument posited at the outset that resources are undifferentiated and these results reflect the difficulty of the mental rotation task. From the perspective of unitary resource theory, one could argue that the mental rotation task was quite difficult and required so much mental effort that even the apparently very easy 1-back showed a decrement in performance.

An alternative explanation may be found in the work of Logie and Salway (1990). They reported evidence that the mental rotation of 2-dimensional figures relies on visuospatial resources, but even more heavily on executive resources. From this perspective, the interpretation of these results would be that the mental rotation task interferes with the n-back tasks to the extent that both require executive resources. Because the decrement was larger in the 3-back than in the 1-back, it could be concluded that the 3-back places a larger demand on executive resources than does the 1-back. This would be consistent with the conclusions of experiments 1 and 2 in which the 3-back showed a clear decrement in performance when paired with another 3-back, but when the 1-back was paired with another 1-back, the participants showed largely spared performance in accuracy but some slowing of reaction time.

The results of the RKG tasks are difficult to reconcile with any perspective of dual-task performance. It is surprising that there is no evidence that the RKG task interfered with the *n*-back tasks at all. Given the literature on the task, it certainly appears to tax executive resources, or at the very least to be a difficult, attention-demanding task. Informal debriefing of the participants in this study revealed that they, too, found the task challenging. One possibility is that participants did not get enough practice on the task in the single-task condition for stable performance to have developed. According to Marsh and Hicks (1998), typical single-task scores on the redundancy measure are around .3 and their participants scored close to .4 in their dual-task conditions. In contrast, the participants in this study scored on average .57 in the single-task and .61 in the dual-tasks. There was a slight trend in the 3-back dual-task condition for there to be a decrement in performance of both tasks, but neither of those trends

reached significance. It may be that with greater practice on the single-task that less variability would be seen in the single-task performance and perhaps this would lead to a significant difference between the single and 3-back dual-task conditions.

Overall, the results of this study cannot exclude the possibility that the results of experiments 1 and 2 are simply due to lesser and greater difficulty in the various levels of the *n*-back. They do, however, suggest that all of these tasks are complex and none are pure measures of any cognitive process, a point that will be expounded upon further in the general discussion.

Figures

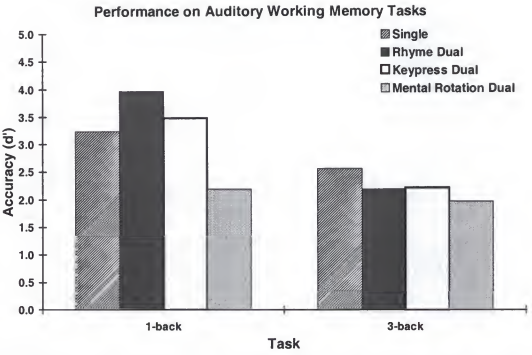

Figure 9. Accuracy for the auditory working memory *n*-back tasks in the single condition and with various secondary tasks.

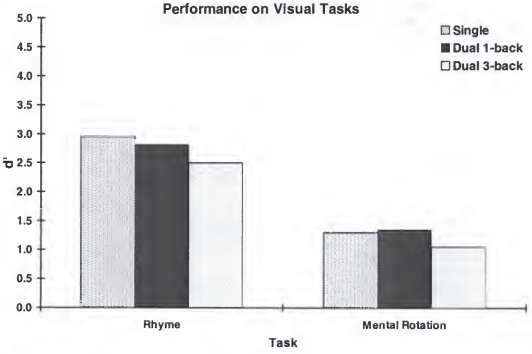

Figure 10. Accuracy for the visual rhyme and mental rotation tasks in single-task and dual-task conditions.

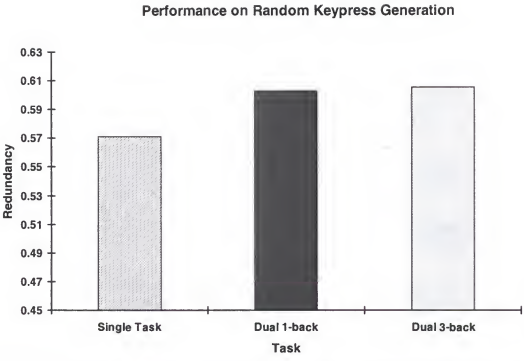

Figure 11. Redundancy on the random keypress generation task when performed as a single-task and as dual-tasks.

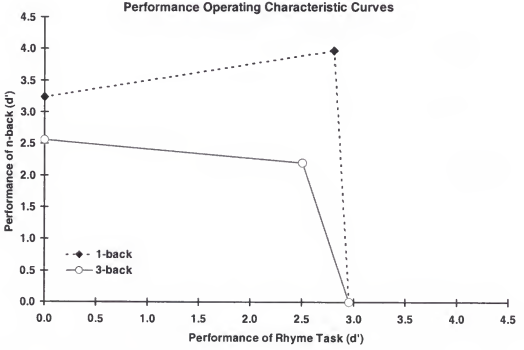

Figure 12. Performance Operating Characteristic curves for the *n*-back tasks when paired with the rhyme judgment task.

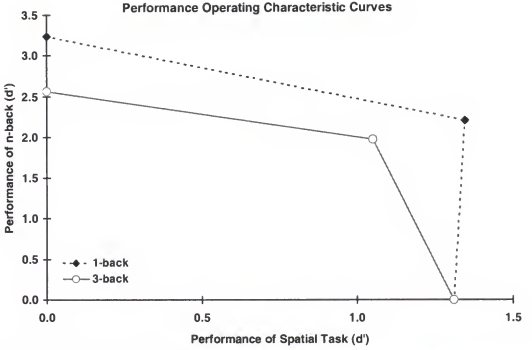

Figure 13. POC curves for the *n*-back tasks when paired with the mental rotation task.

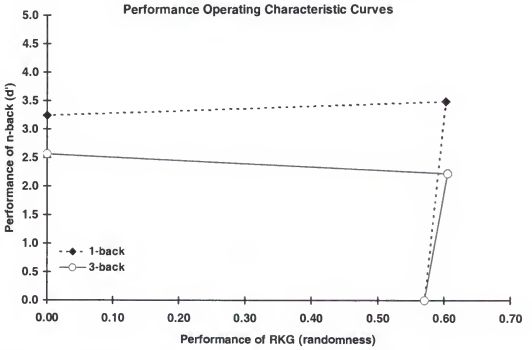

Figure 14. POC curves for the *n*-back tasks when paired with the random keypress generation (RKG) task.

CHAPTER 5
GENERAL DISCUSSION

The three studies presented in this paper have been concerned with the question of the extent to which the central executive is required to carry out the various versions of the *n*-back task. This task has been utilized in many neuroimaging studies of working memory, but the cognitive processes required to perform the task have seldom been studied from an experimental cognitive psychology perspective. Rather, the processes involved in the task have been presumed from the patterns of brain activations in the neuroimaging studies referred to earlier. Specifically, Smith and Jonides (e.g., Smith and Jonides, 1997) have consistently found that the DLPFC activates in the 2- and 3-back tasks, but much less so in the 0- and 1-back task, which lead to the interpretation that the higher levels of *n* require executive processes while the lower levels of *n* do not.

The first two experiments presented in this paper largely support the notion that the 2- and 3-back tasks require executive resources and that the 0- and 1-back require little or no executive resources. This is seen in the pattern of reduced accuracy and extended reaction time for the 2- and 3-back tasks when they are paired in a dual-task situation in experiments 1 and 2. There was some evidence that the 1-back task may require executive resources, though perhaps to a smaller degree than the 2- and 3-back, as seen in trends toward reduced accuracy and longer reaction times in the auditory task of experiment 1 and both the visual and auditory tasks of experiment 2. The third experiment challenges the notion that these resources are necessarily executive resources

and the suggestion that a unitary resource model could account for the results of experiments 1 and 2 could not be refuted. Nonetheless, the results of experiment 3 indicate that the *n*-back is a multifaceted task that produces a complex pattern of interference in dual-task situations.

The results of these experiments are largely consistent with the neuroimaging findings of Smith and Jonides (1997), but the suggestion that the 1-back may require executive processes, albeit to a lesser degree than the higher levels of *n*, is not consistent with the activation patterns of the DLPFC. If the DLPFC is involved in the operation of the central executive, there still remains the question of why some level of activation in the range between that of the 0-back and the 2-back has not been found. The solution may lie in the need to segment the central executive into multiple components. It is possible, perhaps even likely, that the executive processes needed by the 1-back are qualitatively different from the executive processes required by the 2- and 3-back. Perhaps the DLPFC is an integral part of a network that subserves those processes required by the 2- and 3-back, and perhaps some other brain region or regions are involved in the executive processes required by the 1-back.

In the introduction to this paper, a few of the ways in which the central executive has been explored were reviewed. From the variety of studies presented in this paper, it is clear that the concept of "executive processes" is multifaceted, and the results of these studies reinforce this multiplicity. Different conceptions of executive processes include such functions as the simultaneous storage and manipulation of information in WM, the temporal sequencing of events, the coordination of information from the slave systems, the control of attention, broadly defined. There is also evidence that executive functions

may be related to prospective memory and general intelligence. It has also been shown that traditionally, executive functions have been highly tied conceptually to anatomical locations within the brain, namely the frontal lobes, but that conceptualization is changing as an emphasis on coordinated networks of both cortical and subcortical structures begin to be understood as necessary for a variety of "higher" cognitive processes.

Many questions remain regarding the central executive and the possible need to subdivide it into independent but related concepts. Recently, Smith and Jonides (1999) presented a brief overview of some of the findings relating to the cognitive neuroscience of working memory. They conclude that sufficient evidence from lesion and neuroimaging studies exists to support the hypothesis that executive processes can be divided into at least five independent functions: 1) attention and inhibition, 2) task management, 3) planning, 4) monitoring, and 5) temporal and spatial coding. While they mention specifically neuroanatomical data to support these divisions, the experimental tasks presented in this paper, to varying degrees, involve these abilities and skills.

Smith and Jonides (1999) define the executive function of "attention and inhibition" as "focusing attention on relevant information and processes and inhibiting irrelevant ones" (p. 1659). The prototypical example of the operation of this function is seen in the Stroop task. An aspect of this function can be seen in Morris and Jones' (1990) updating of working memory task. In order to succeed on lists longer than 6 items, the participant would need to "discard" the initial items and to retain the new items, in a sense, inhibiting the no longer relevant information. The *n*-back task, for the

same reason, can be seen as requiring an inhibition of information that is no longer relevant.

By "task management" Smith and Jonides (1999) mean the coordination or allocation of resources when faced with a dual-task situation. Although Klingberg (1998) concluded that there was no brain region specific to all dual-task situations, Smith and Jonides cite evidence that the DLPFC mediates the coordination of resources in a dual-task situation. This is in accord with the suggestion by Wickens (1984) that time-sharing, or the actual coordination of resources, is itself a skill or ability.

Smith and Jonides (1999) defined "planning" as the creation of a sequence of subtasks in order to accomplish a larger goal. Although not explicitly discussed in this paper, the Towers of London and Hanoi are common clinical tools for the investigation of executive functions in patients. These sorts of multi-step problems are the prototypical tasks requiring subgoaling. Although the two cannot be equated, prospective memory clearly relates to planning. If planning is the creation of the subgoals, the next step in accomplishing a complex task is to remember to carry out those subgoals. It seems reasonable that both processes should require the intervention of the central executive.

The fourth executive function delineated by Smith and Jonides (1999) was what they called "monitoring." By this, they meant the updating of and checking the contents of working memory. Baddeley (1996) listed "retrieval checking" as among the processes for which the central executive should be responsible. Morris and Jones (1990) considered the updating of working memory to involve the central executive, and for the same reason, as stated above, so should the *n*-back task. Random generation may require this function, as it may be responsible for what Baddeley called "switching retrieval

plans." At the least, this would be the function responsible for checking the output of the retrieval plan for randomness prior to its being released as an overt response.

The final executive function is what Smith and Jonides (1999) termed "coding" and by this they meant the spatial- or temporal-tagging of information. This function can be seen most clearly in the *n*-back task. In order to accomplish the task, the participant must make note of the point in time in which each stimulus was presented. The spatial version of the task (in which a key is to be pressed when the current stimulus is present in the same location as the stimulus n stimuli back) makes use of both temporal coding and spatial coding.

The multitudes of experimental tasks that have been utilized to investigate the central executive have in common the fact that they are very complex and multifaceted tasks. If an understanding of this most fundamental of cognitive concepts is to be gained, it will likely require a careful consideration of the basic components of these many multifaceted tasks. The segmenting and terminology used by Smith and Jonides (1999) is just one approach, and they acknowledge that there is little consensus regarding the exact boundaries. Neuropsychological and neuroimaging studies can help us determine what brain regions are most related to these different tasks and in the process help us determine where those boundaries need to fall. The psychometric approach to the central executive will be most useful when the patterns of individual differences on these various central executive tasks are examined, and through careful experimental design, the dual-task paradigm and other creative experimental approaches may help us segment these complex tasks into their more basic components, and in so doing, segment the central executive.

APPENDIX
STIMULI AND INSTRUCTIONS

Stimulus Sentences for Daneman and Carpenter's Listening Span Test

Sets of 2 sentences:
Due to his gross inadequacies, his position as director was terminated **abruptly**.
It is possible, of course, that life did not arise on the earth at **all**.

Jane's relatives had decided that her gentleman friend was not one of high **status**.
Without hesitation, he plunged into the difficult mathematics assignment **blindly**.

Sets of 3 sentences:
The devastating effects of the flood were not fully realized until months **later**.
In a moment of complete spontaneity, she developed a thesis for her **paper**.
At the conclusion of the musicians' performance, the enthusiastic crowd **applauded**.

They attended the theater habitually except for circumstances beyond their **control**.
The lumbermen worked long hours in order to obtain the necessary amount of **wood**.
The old lady talked to her new neighbor on her weekly walks from **church**.

Sets of 4 sentences:
I found the keynote speaker incredibly boring, inarticulate and not well **read**.
In order to postpone the business trip, he canceled his engagements for the **week**.
The incorrigible child was punished brutally for his lack of respect for his **elders**.
The brilliant trial attorney dazzled the jury with his astute knowledge of the **case**.

The smokers were asked to refrain from their habit until the end of the **production**.
The young business executive was determined to develop his housing projects within the **year**.
Despite the unusually cold weather, the campers continued their canoe **trip**.
All students that passed the test were exempt from any further seminars that **semester**.

Sets of 5 sentences:
A small oil lamp burned on the floor and two men crouched against the wall, watching **me**.
The products of digital electronics will play an important role in your **future**.
One problem with this explanation is that there appears to be no defense against **cheating**.
Sometimes the scapegoat is an outsider who has been taken into the **community**.
I should not be able to make anyone understand how exciting it all **was**.

In a flash of fatigue and fantasy, he saw a fat Indian sitting beside a **campfire**.
The lieutenant sat beside the man with the walkie-talkie and stared at the muddy **ground**.
I will not shock my readers with a description of the cool-blooded butchery that **followed**.
The courses are designed as much for professional engineers as for amateur **enthusiasts**.
The taxi turned up Michigan Avenue, where they had a clear view of the **lake**.

Sets of 6 sentences:

The announcement of it would resound throughout the world, penetrate to the remotest **land**.
To do so in directions that are adaptive for mankind would be a realistic **objective**.
Slicing it out carefully with his knife, he folded it without creasing the **face**.
He laughed sarcastically and looked as if he could have poisoned me for my **errors**.
He tolerated another intrusion and thought himself a paragon of patience for doing **so**.
The reader may suppose that I had other motives, besides the desire to escape the **law**.

He listened carefully because he had the weird impression that he knew the **voices**.
The basic characteristic of the heroes in the preceding story is their **sensitivity**.
His imagination had so abstracted him that his name was called twice before he **answered**.
He had an odd elongated skull which sat on his shoulders like a pear on a **dish**.
He stuffed his denim jacket into his pants and fastened the stiff, new snaps **securely**.
On the desk where she wrote her letters was a clutter of objects coated in **dust**.

Sets of 7 sentences:

He had patronized her when she was a schoolgirl and teased her when she was a **student**.
The rain and howling wind kept beating against the rattling **windowpanes**.
He covered his heart with both hands to keep anyone from hearing the noise it **made**.
The stories all deal with a middle-aged protagonist who attempts to withdraw from **society**.
Without tension there could be no balance either in nature or in mechanical **design**.
I wish there existed someone to whom I could say that I felt very **sorry**.
The entire town arrived to see the appearance of the controversial political **candidate**.

After passing all the exams, the class celebrated for an entire week without **resting**.
According to the results of the survey, Robert Redford is the most liked Hollywood **star**.
The weather was unpredictable that summer so no one made plans too far in **advance**.
There are days when the city where I live wakes in the morning with a strange **look**.
We boys wanted to warn them, but we backed down when it came to the **pinch**.
With shocked amazement and appalled fascination Marion looked at the **pictures**.
He stood there at the edge of the crowd while they were singing, and he looked **bitter**.

Stimuli and Apparatus for the Modified Corsi Block-tapping Task

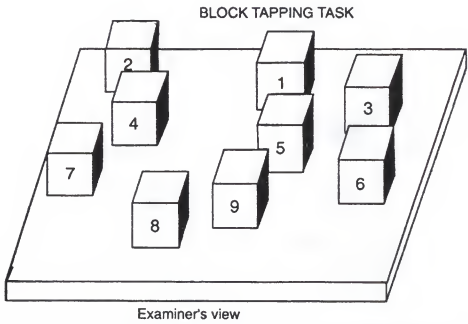

Figure 15. Diagram of apparatus used in the modified Corsi Block-tapping Task

Sequences for the Modified Corsi Block-tapping Task

Sets of 2:
5-2-8-**3**
6-4-1-**7**

5-8-3-**2**
9-5-2-**8**

Sets of 3:
9-7-8-**1**
9-3-4-**5**
8-2-7-**6**

3-9-4-**3**
7-2-4-**1**
8-7-5-**9**

Sets of 4:
2-6-8-**6**
4-1-7-**5**
8-5-7-**3**
2-6-5-**1**
1-8-7-**3**
4-6-2-**9**
8-4-9-**5**
6-7-2-**1**

Sets of 5:
2-6-8-**4**
2-7-5-**8**
1-6-3-**2**
9-4-2-**6**
1-5-3-**4**

9-4-6-**1**
3-5-1-**7**
2-1-7-**9**
8-5-4-**7**
3-6-1-**4**

Sets of 6:
8-9-2-**5**
3-4-1-**6**
4-2-6-**8**
3-7-5-**9**
5-6-3-**8**
7-4-2-**1**

6-7-4-**2**
8-5-3-**9**
7-4-6-**8**
5-3-1-**8**
9-4-1-**6**
5-2-4-**1**

Instructions for the Random Keypress Generation Task

You will see a small white cross on the computer screen. Throughout the experiment, you should keep your eyes focused on that white cross in the center of the screen. Then you will see a series of small squares in various locations around the fixation cross. Your task in this part is to produce a random string of key-presses.

What exactly do I mean by a "random string of key-presses"? As an illustration, let's imagine that we wanted to produce a random list of colors. In any random sequence all of the possible items occur approximately equally often, and the item that follows any given item is not predictable. In other words if we had a list of colors, and blue always followed green, then anytime we saw green in the list, we could predict that the next color would be blue. This would not be a random list of colors. Imagine that you have a hat with 8 differently colored ping-pong balls. Imagine that you shake the hat and draw one of the ping-pong balls from the hat, say aloud the color of the ping-pong ball, and then replace the ping-pong ball into the hat again. Imagine that you again shake the hat containing the 8 ping-pong balls, draw one out, say the name of the color, and then replace the ball into the hat again. Imagine that you repeat this process over and over again. In doing so, you would be creating a random string of colors.

We'd like for you to perform a similar act in this task, but you won't have a hat with differently colored ping-pong balls. Instead we'd like for you to attempt to produce a random string of key-presses by pressing any one of 8 keys that you choose each time a square comes up on the computer screen (I'll tell you which 8 keys you'll be using in a moment). Over the course of the session your list of responses should be random, that is, you should try to use all 8 keys equally often and you should try to avoid pressing the

keys in any pattern that would make any given response predictable based on the response that it follows.

Please place your hands on the keyboard as if you were going to type, with your left index finger over the "f" key and your right index finger over the "j" key. Please move your index fingers lightly over the surface of the keys. Feel that little ridge on the keys? Use the feeling of that little ridge as a cue to know that your fingers are in the right position on the keyboard. You will use the 8 "home row" keys that are now beneath your pinkie, ring, middle, and index fingers on both hands to perform this task.

Each time a square comes up on the computer screen, you should choose one of the 8 keys at random and press it as quickly as possible. The squares come up at a rate of one per second. This is a rather fast pace, so you don't have very much time in which to make a response. Try to make a response to every square. The location of the square on the screen is irrelevant; it changes only to prevent you from seeing an intense "after-image" of the square.

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BIOGRAPHICAL SKETCH

Michelle R. Simmons was born February 24, 1971 in Fort Myers, Florida. She grew up primarily in Bradenton, Florida where she attended Manatee High School. In 1989, she was designated a National Merit Scholar and began her undergraduate career at the University of Florida. She received her Bachelor of Science degree in psychology from UF in 1995 and in August 1995, she began graduate school in the Department of Psychology at UF. She received her Master of Science degree in August 1998 and will receive her Doctor of Philosophy degree in August 2000. In November 1999 she was awarded a College of Liberal Arts and Sciences Dissertation Fellowship for the Spring 2000 semester, and in January 2000 she received a Sigma Xi grant-in-aid-of research award to conduct follow-up studies to the work presented in this dissertation. After she completes her Ph.D. she will begin working full-time as a post-doctoral researcher at Carnegie Mellon University in Pittsburgh, Pennsylvania under the direction of Lynne Reder.

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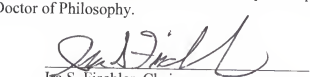

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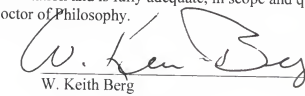

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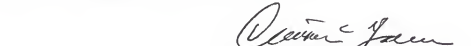

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This dissertation was submitted to the Graduate Faculty of the Department of Psychology in the College of Liberal Arts and Sciences and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

August 2000

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